Absorption Imaging
-
2D & 3D

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ESRF

ID22 Beamline

Talk outline

- **Introduction**
- **Absorption Imaging Background**
  - **0D→1D→2D→3D**
  - **Reconstruction basics**
- **Practical considerations**
  - **Alignment**
  - **Acquisition**
  - **Artifacts and artifact correction**
  - **Computing issues**
- **Some examples**
- **Concluding Remarks**

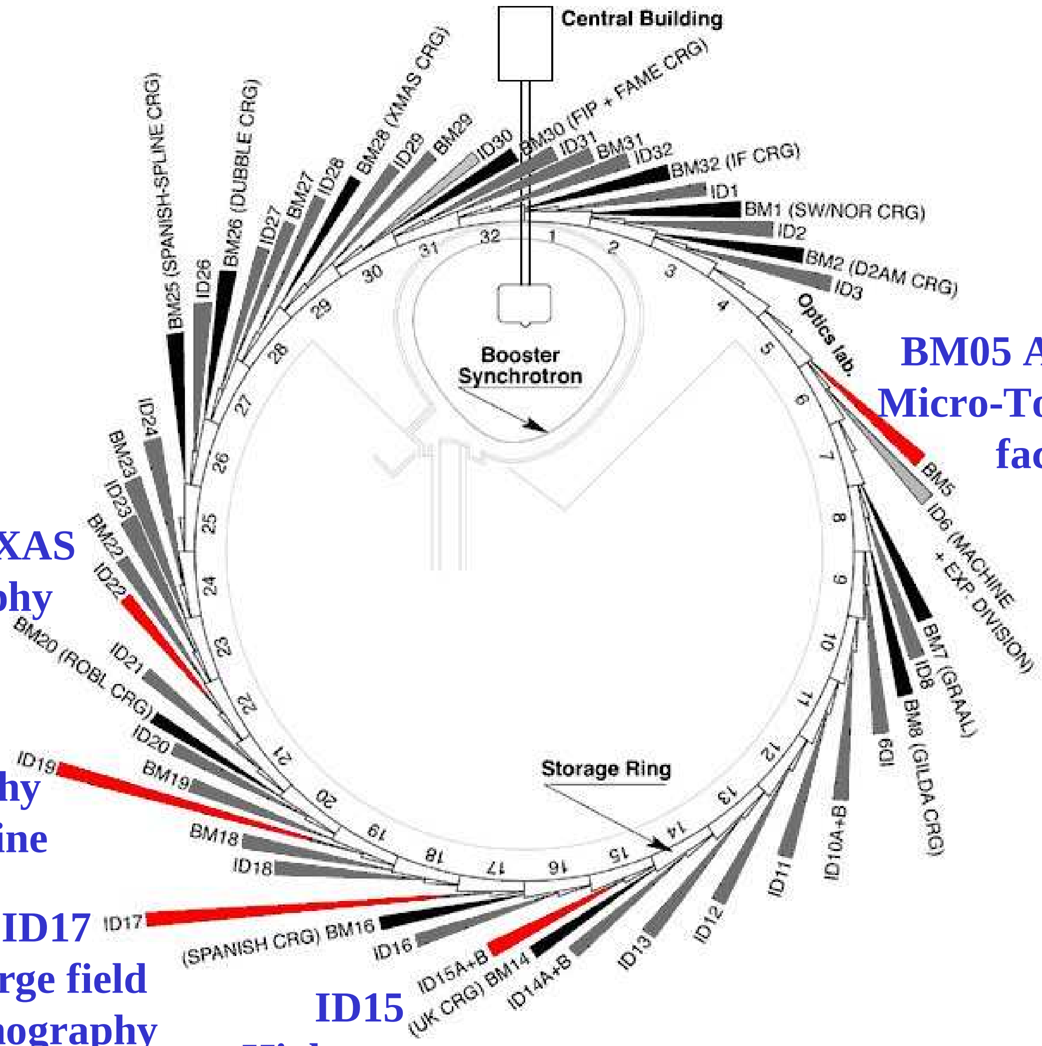
History of Tomography

- **Beginning of Tomography**
  - **Nobel Prize in Physiology or Medicine in 1979 (Cormack &Hounsfield)**
  - **Today, ~ 10 medical scanners /million people (France)**
    ~ 15 medical scanners /million people(Germany)

- **Application to synchrotron radiation**
  - **First suggested by Grodzins, in 1983, today it is routinely used**

- **Main advantages**
  - **Monochromaticity**
  - **High resolution**
  - **Scanning time**

Absorption Tomography @ ESRF



BM05 Additional Micro-Tomography facility

ID22 Micro-XRF/XRD/XAS combined to tomography

ID19 Micro-tomography dedicated beamline

ID17 Large field tomography

ID15 High energy Tomography

μ-FID22

ESRF

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Interaction of X-rays with matter

- **Interaction wave/matter**
  - **Complex refractive index**

$$n = 1 - \delta + i\beta$$

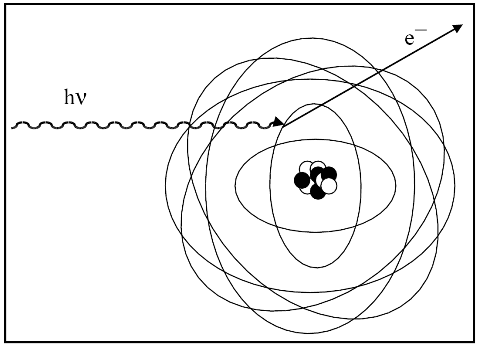
Decrement of the refractive index ≡Phase shift

See P. Cloetens, “*Phase contrast imaging Coherent beams*”, 06/02, 8:30

Absorption index $\mu = \dfrac{4\pi}{\lambda}\beta$

Purpose of this talk

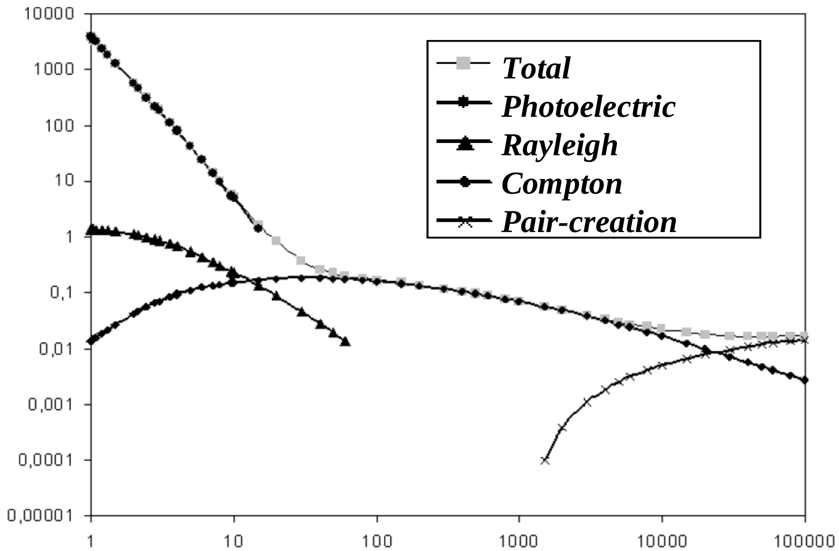
Contributions to attenuation

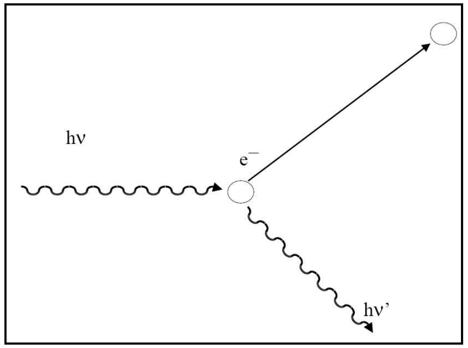


Photoelectric effect

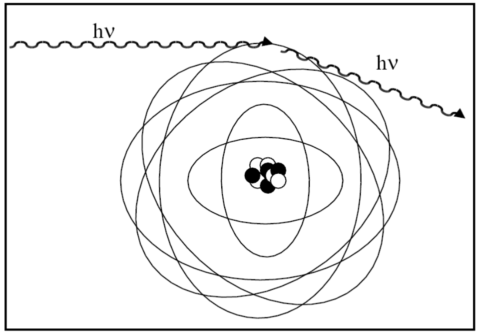
Photons attenuated :

Photons that do not reach a detector placed in the beam axis

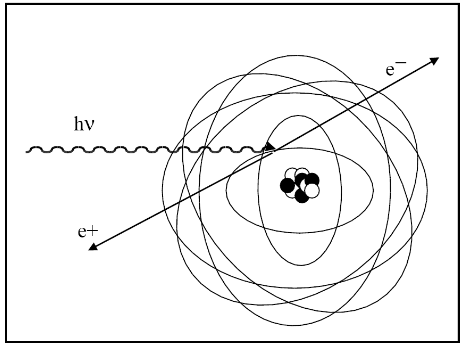




Compton effect

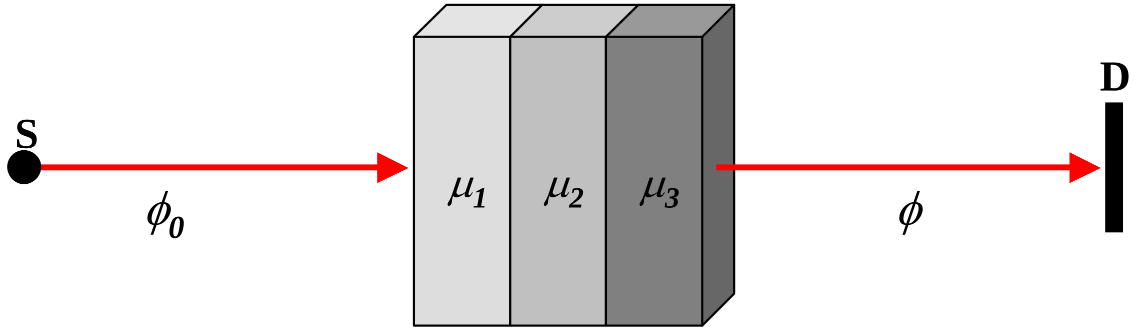


Rayleigh effect



Pair-creation effect (for E > 1MeV)

Beer-Lambert law



Polychromatic case

$$\phi = \int_E \phi_0(E) e^{-\int_{SD} \mu(l,E)dl} dE$$

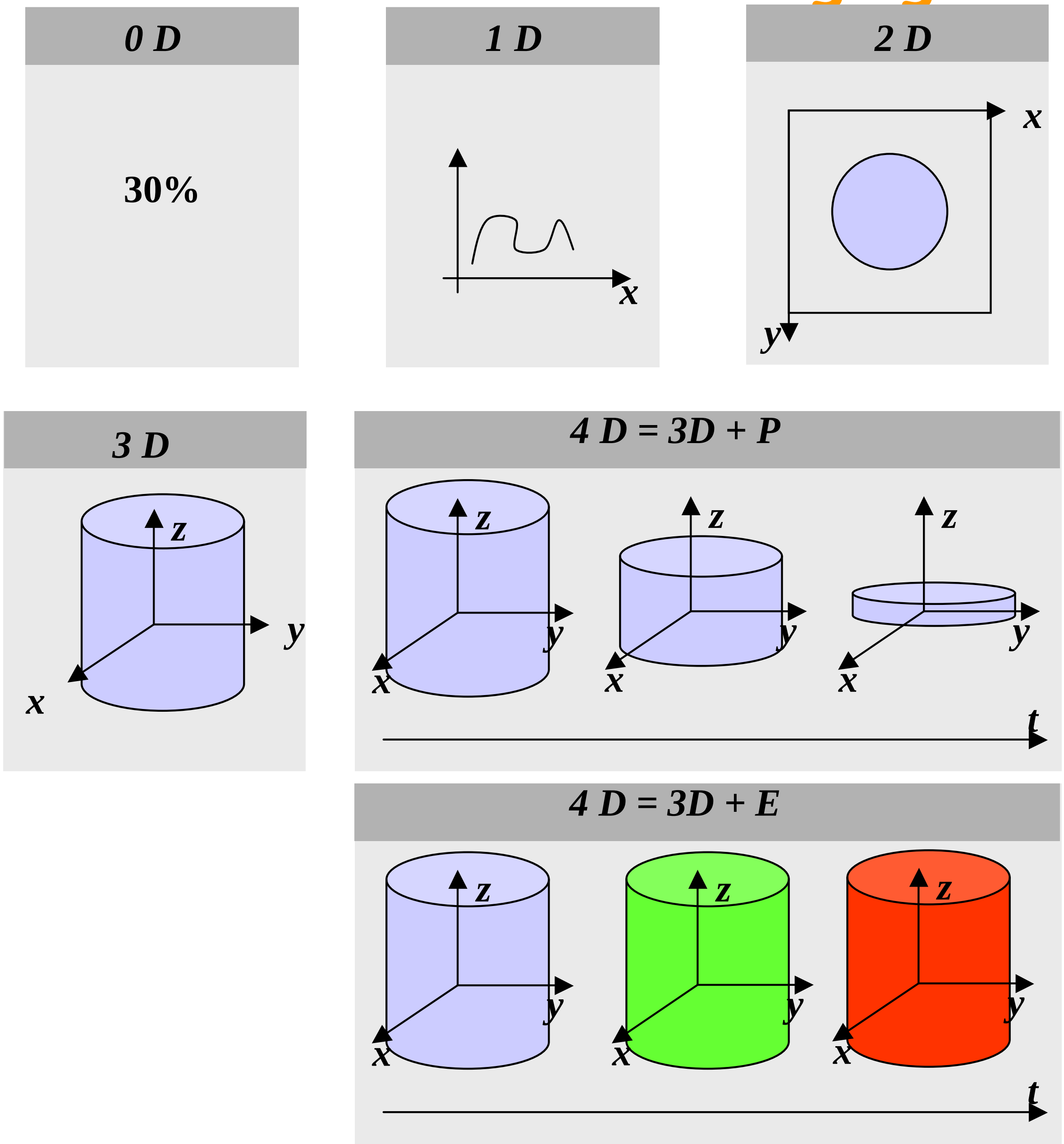
Monochromatic case

$$\phi = \phi_0(E) e^{-\int_{SD} \mu(l,E)dl}$$

Example : E=13 keV

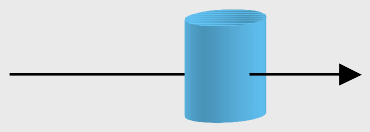
Absorption of 10cm of air ≡Absorption of 200nm of Pb

Multi-dimensional imaging

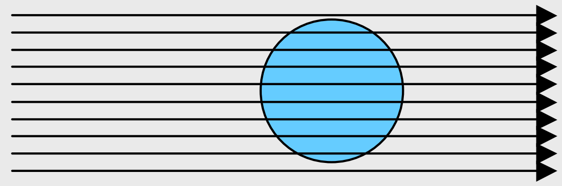


A bit of semantic

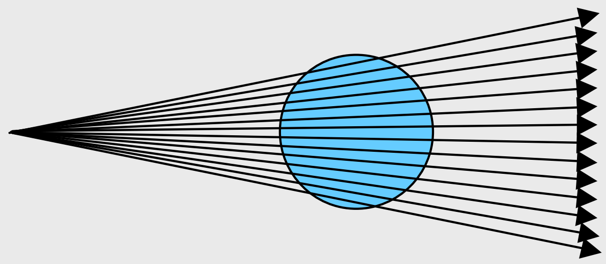
Pencil Beam



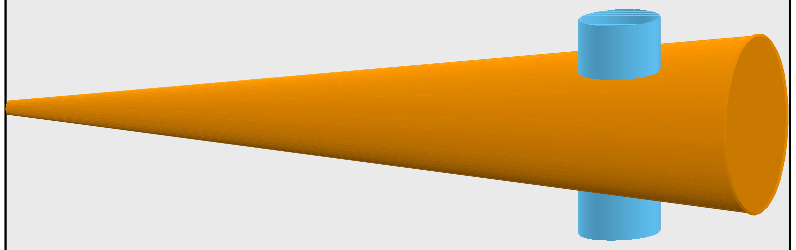
Parallel Beam



Fan Beam

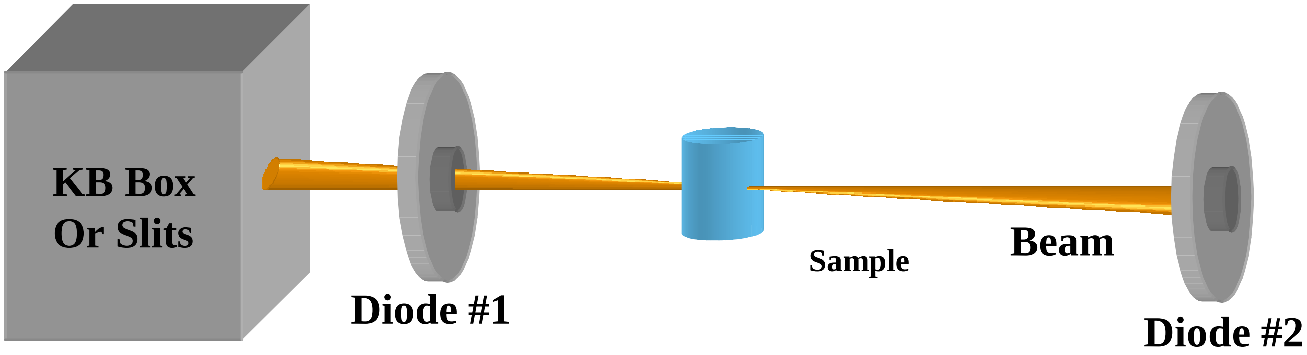


Cone Beam



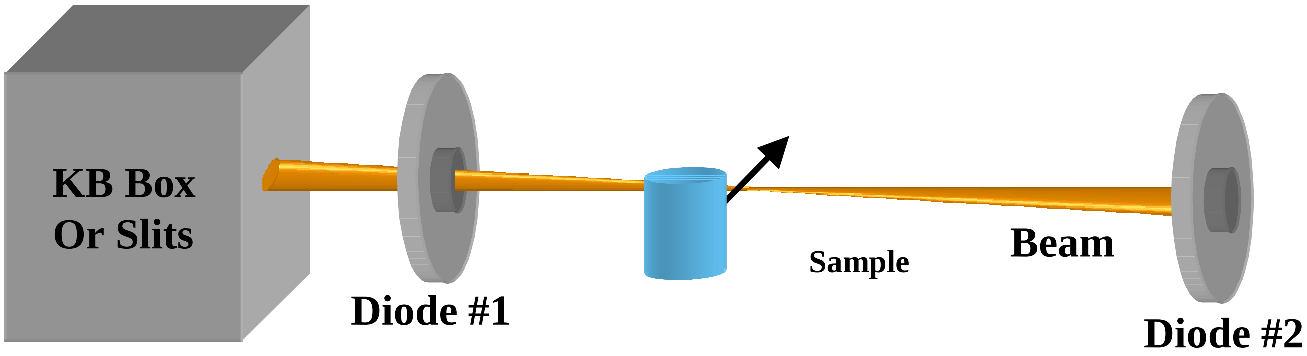
0D

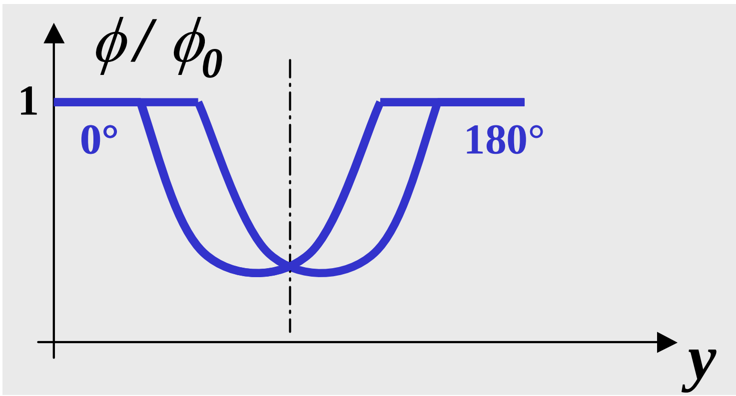
- **Information**
  - **Absorption of the object at some point, *e.g.* 30%**
  - **Used at microfocus beamlines**



1 D

- **Information**
  - Absorption of the object at some point, *e.g.* 30%
  - Used at microfocus beamlines for alignment

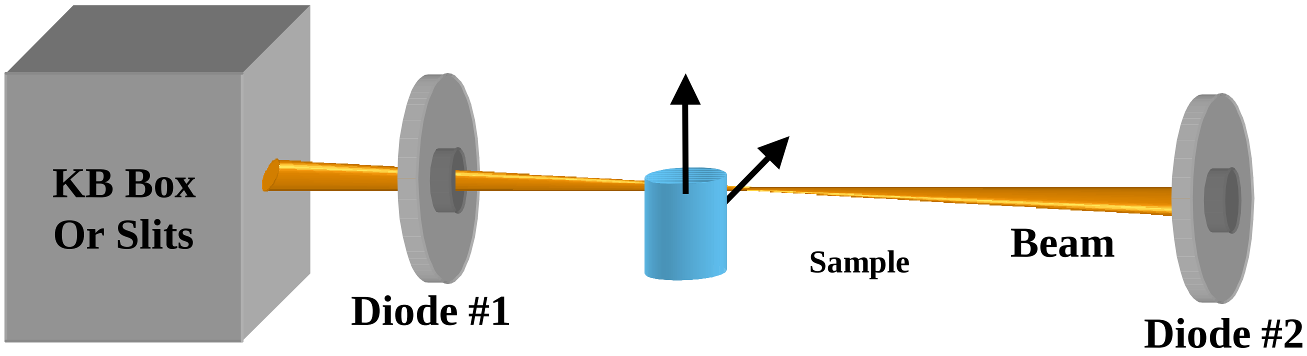


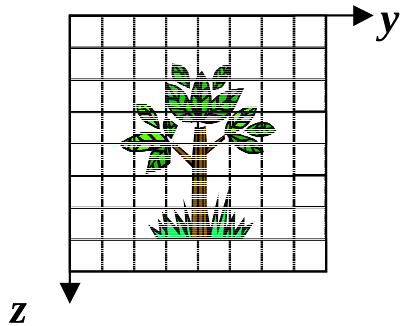


Example : axis of rotation calculation

2 D

- **Information**
  - **Used at microfocus beamlines for mapping**

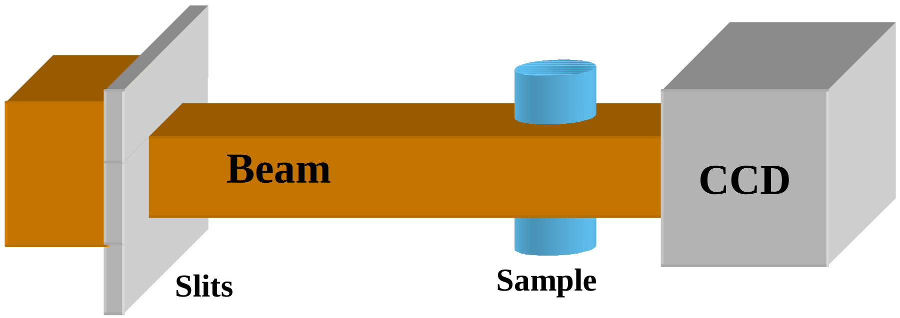


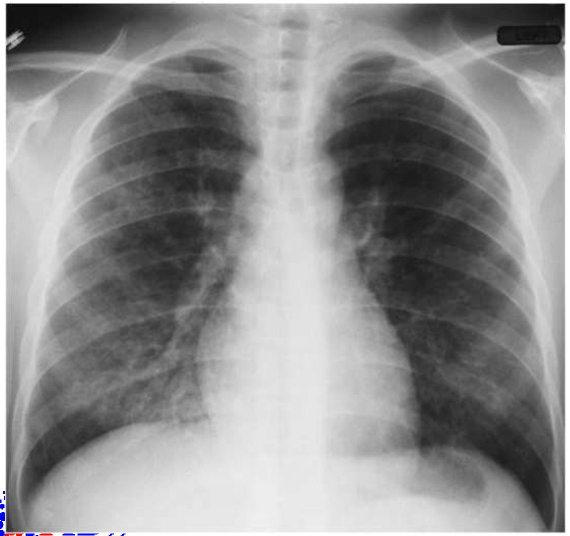


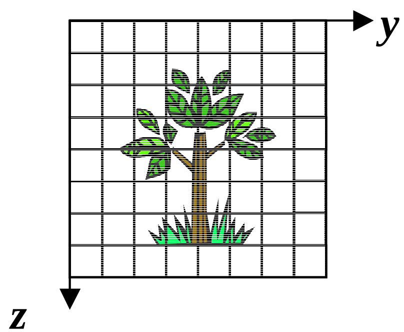
ϕ / ϕ_0 ***2D mapping***

Fast 2D

- **2D detector + full beam**
  - **2D image obtained in a single shot = radiograph**



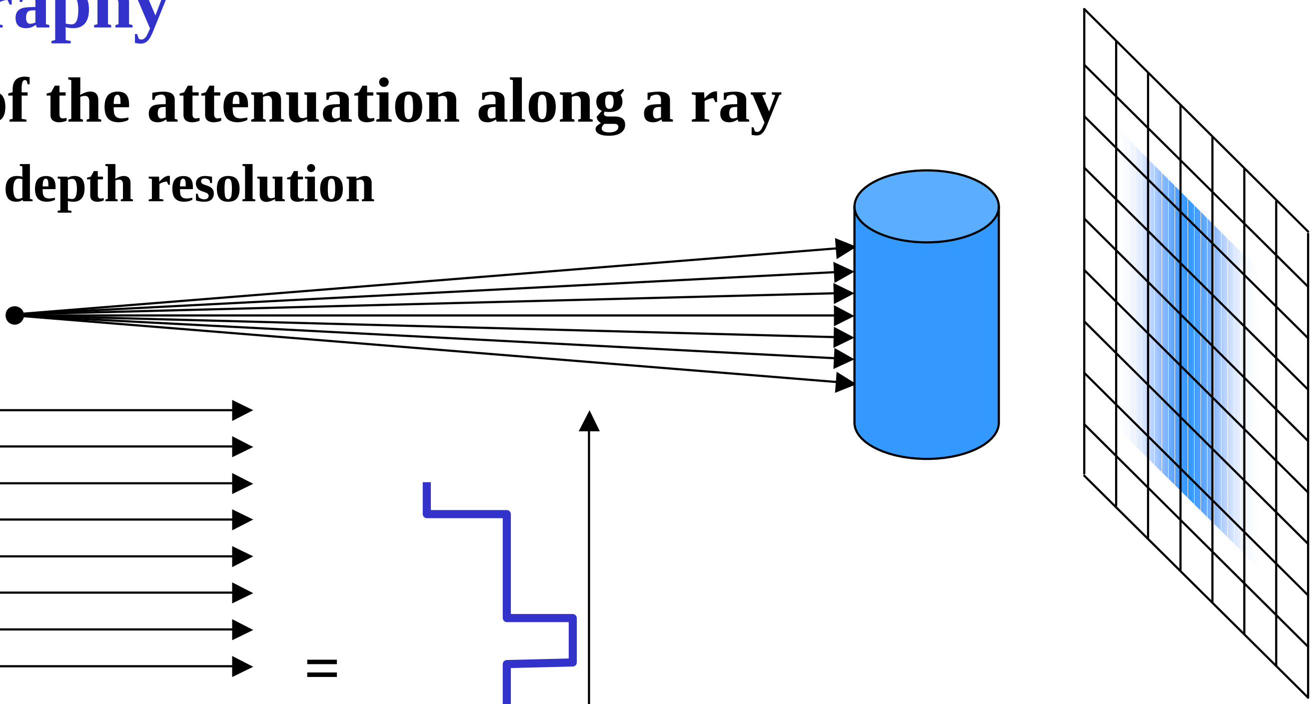


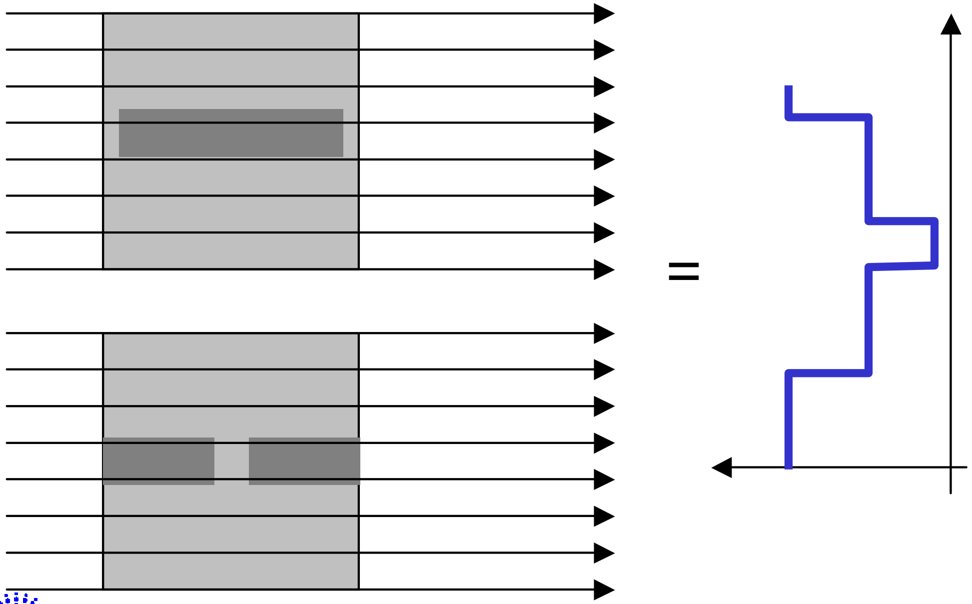


ϕ / ϕ_0 ***2D image***

From 2D to 3D: the reconstruction

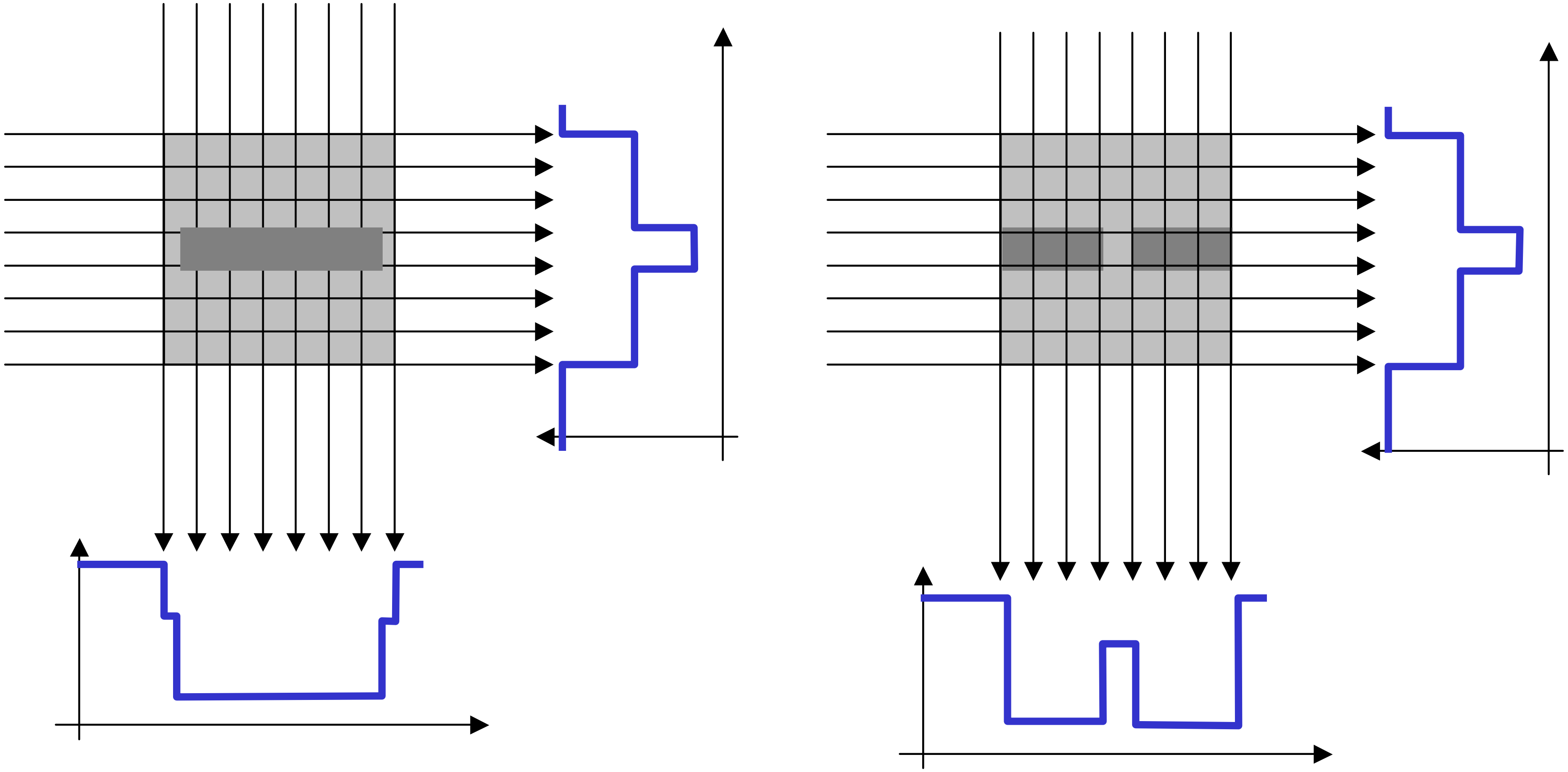
- **Radiography**
  - **Sum of the attenuation along a ray**
    - **→No depth resolution**





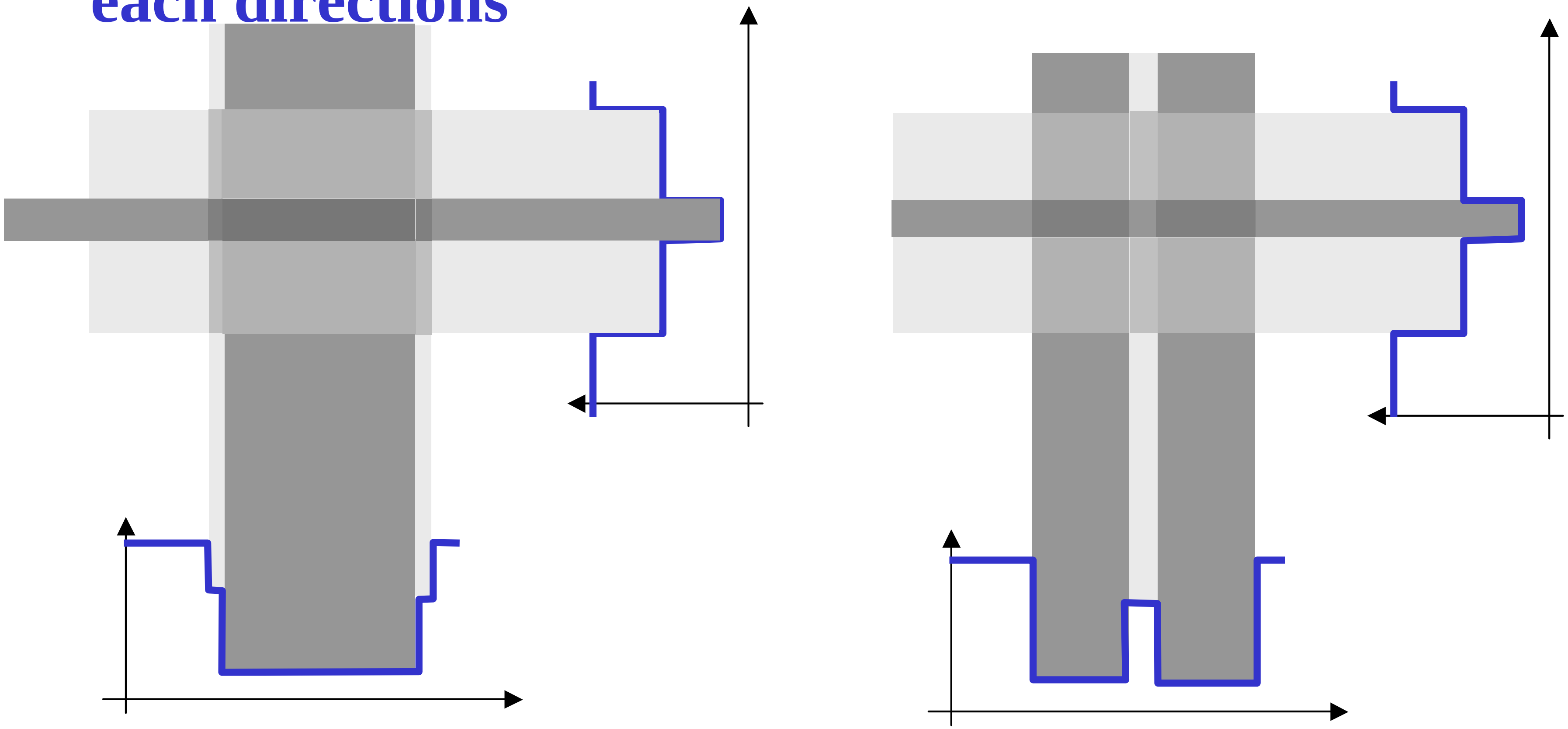
Reconstruction with hands

- To distinguish the 2 : take 2 projections at 90 degrees



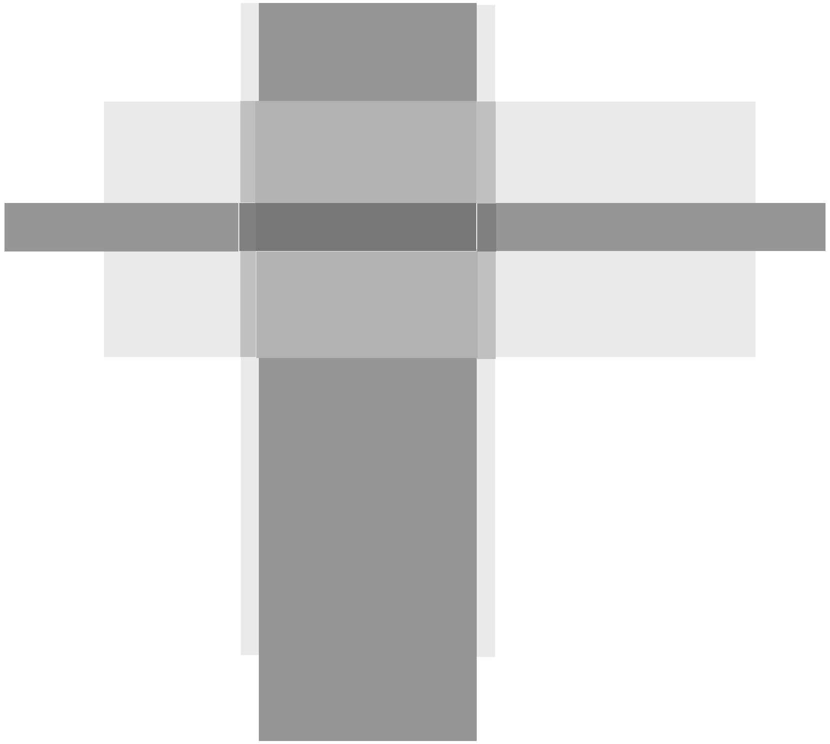
Reconstruction with hands

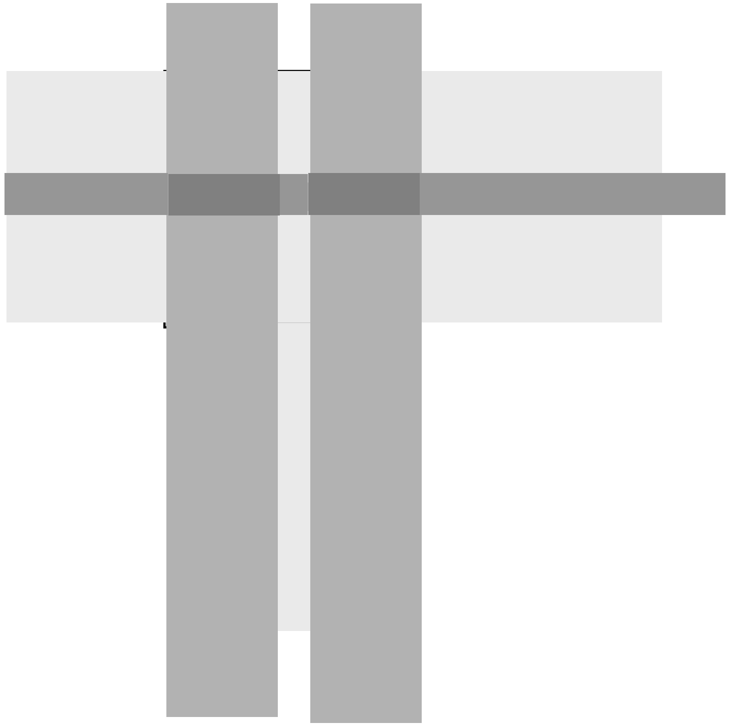
- By "spreading" an summing the 2 projections along each directions



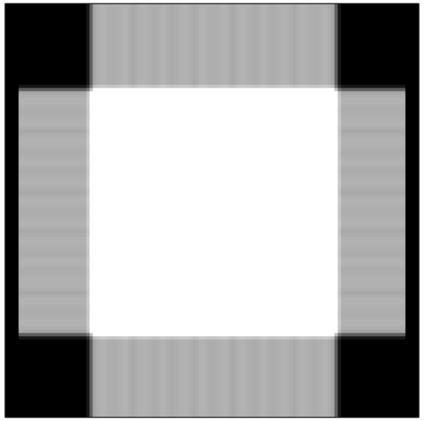
Reconstruction with hands

- 2 projections are not enough !

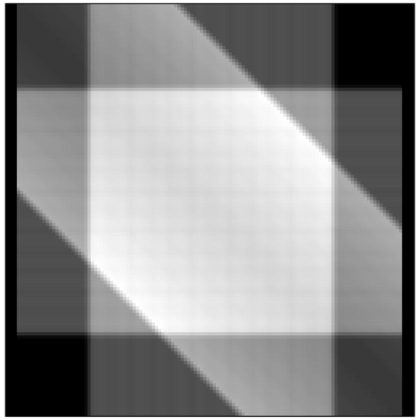




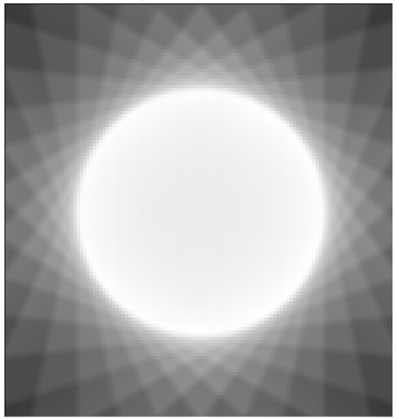
Reconstruction with hands



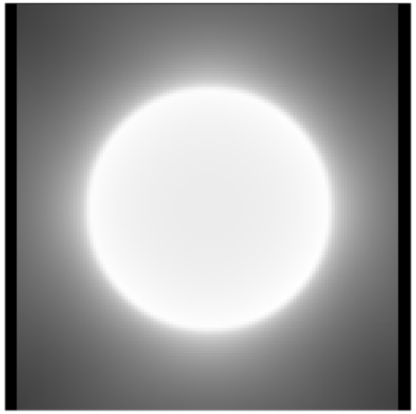
2 projections 0, 90 °



3 projections 0, 45, 90 °

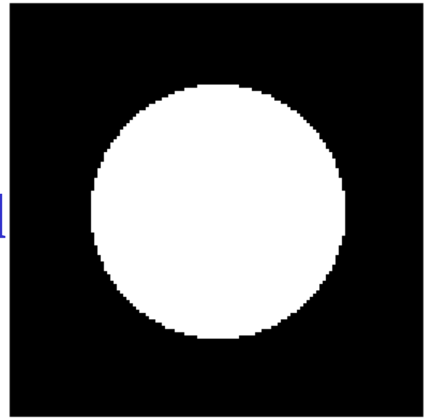


30 projections



1000 projections

- **Still a problem**
  - **Background**
- **Use of a high-pass filter to suppress background**

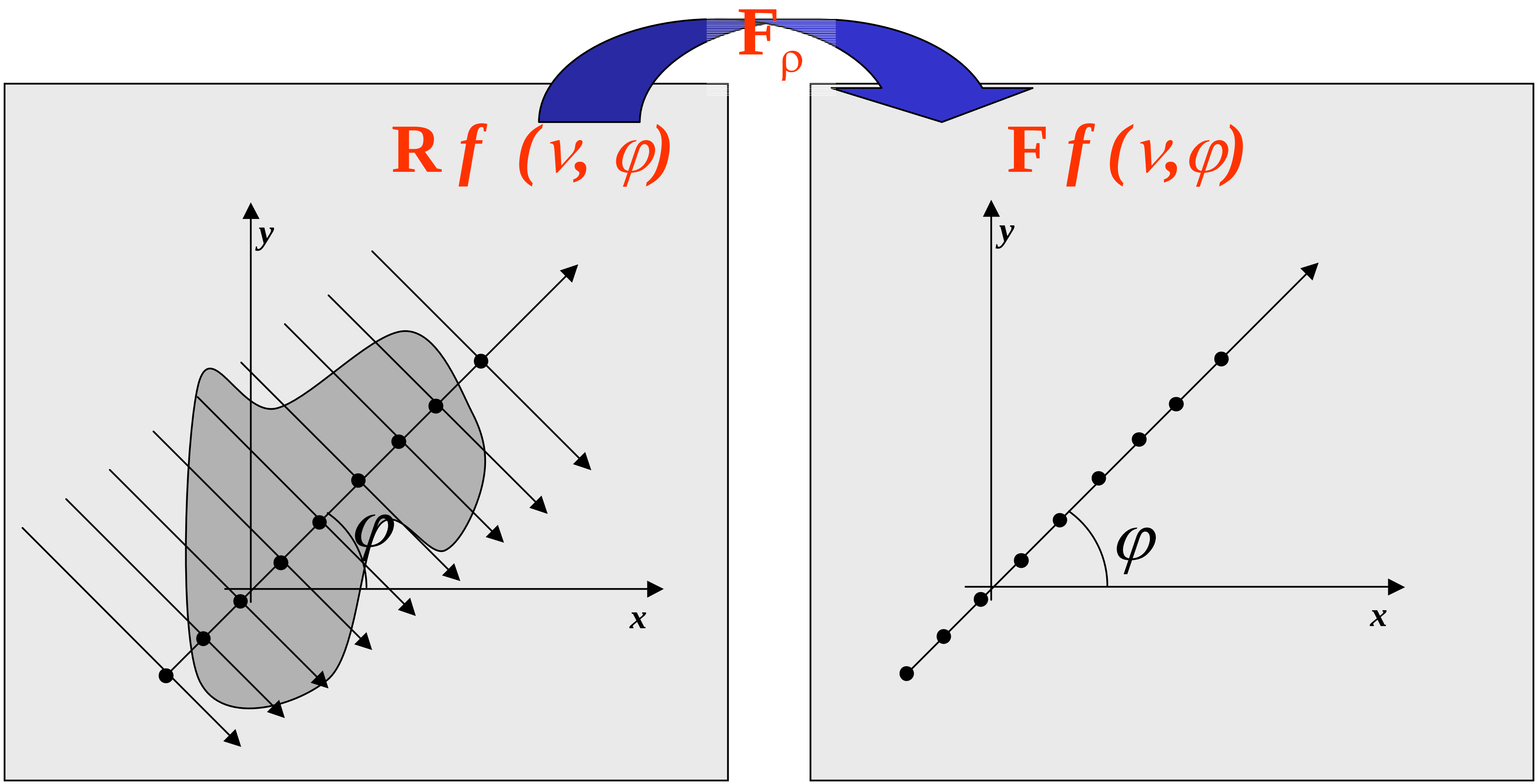


Reconstruction with a brain

- $f(x,y)$……………....Object
- $R\,f(\rho,\ \varphi)$ …………Projection or radiograph of $f(x,y)$ at the angle φ (Radon Transform)
- $F\,f\,(\nu,\varphi)$ ……….. Fourier transform of $f(x,y)$ in polar coordinates
- $F_\rho\,R\,f\,(\nu,\varphi)$ ……..1D Fourier transform of the projection $R\,f(\rho,\ \varphi)$ in polar coordinates at the angle φ

- **Slice-projection theorem** $F_\rho\,R\,f\,(\nu,\varphi) = F\,f\,(\nu,\varphi)$

Slice-theorem : a drawing to get it



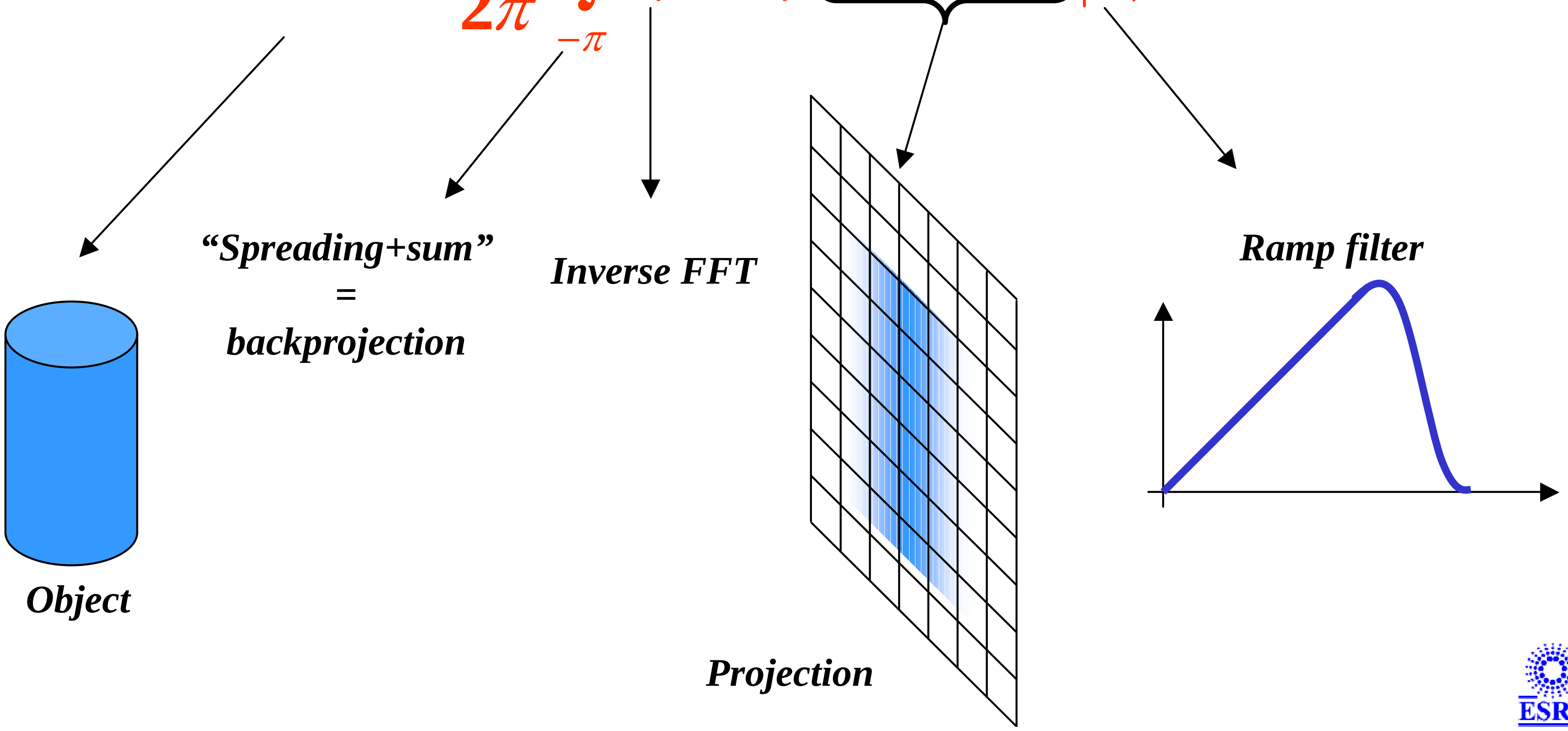
It means :

One can reconstruct the object from its radiographs just by using Fourier transforms…

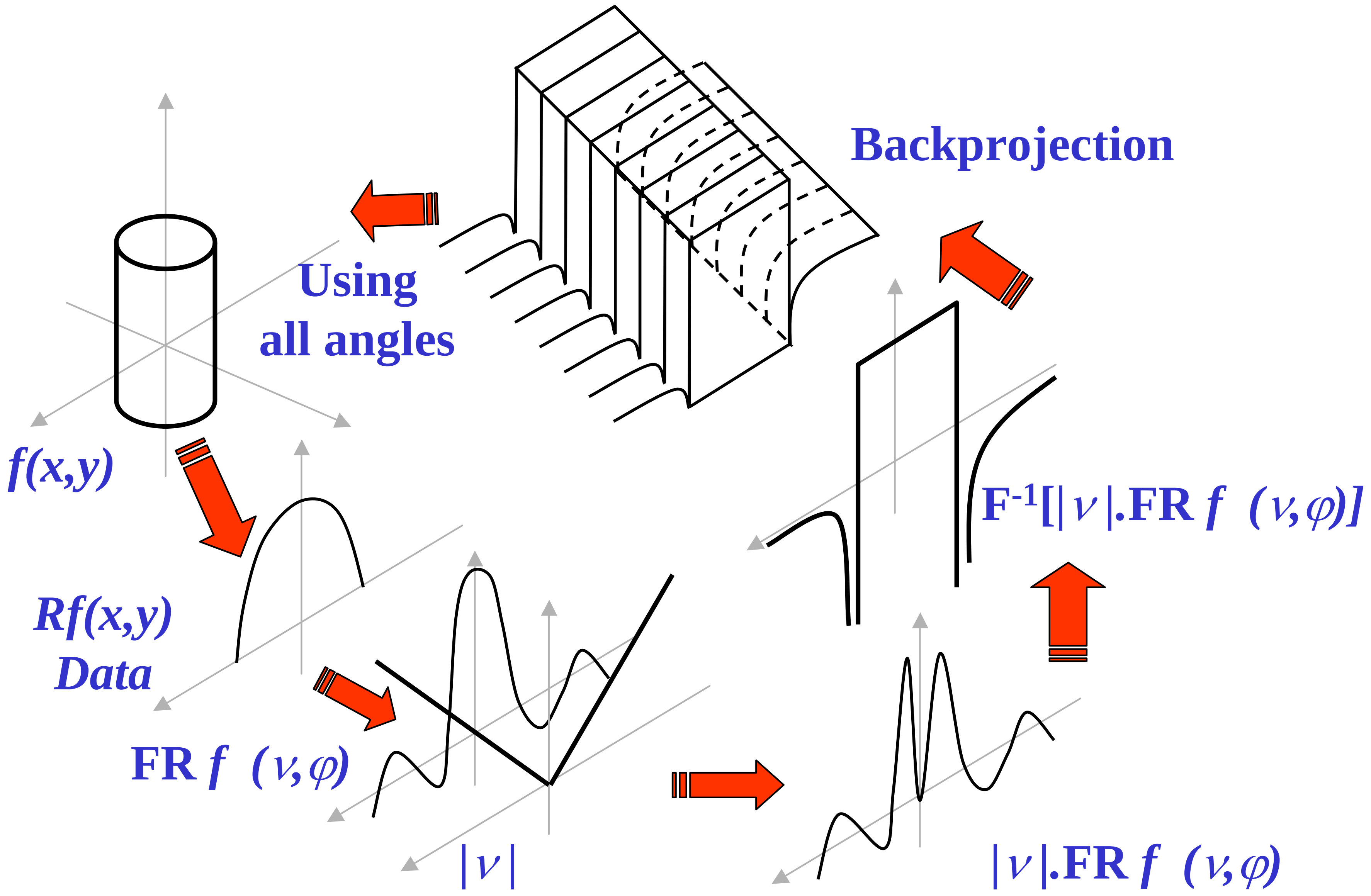
Reconstruction with mathematics

- **From the slice-projection theorem, one can derive the filtered backprojection algorithm (FBP)**

$$f(x,y)=\frac{1}{2\pi}\int_{-\pi}^{\pi}F_{\rho}^{-1}\left[F_{\rho}\underbrace{Rf(\nu,\varphi)}.\left|\nu\right|\right]d\varphi$$

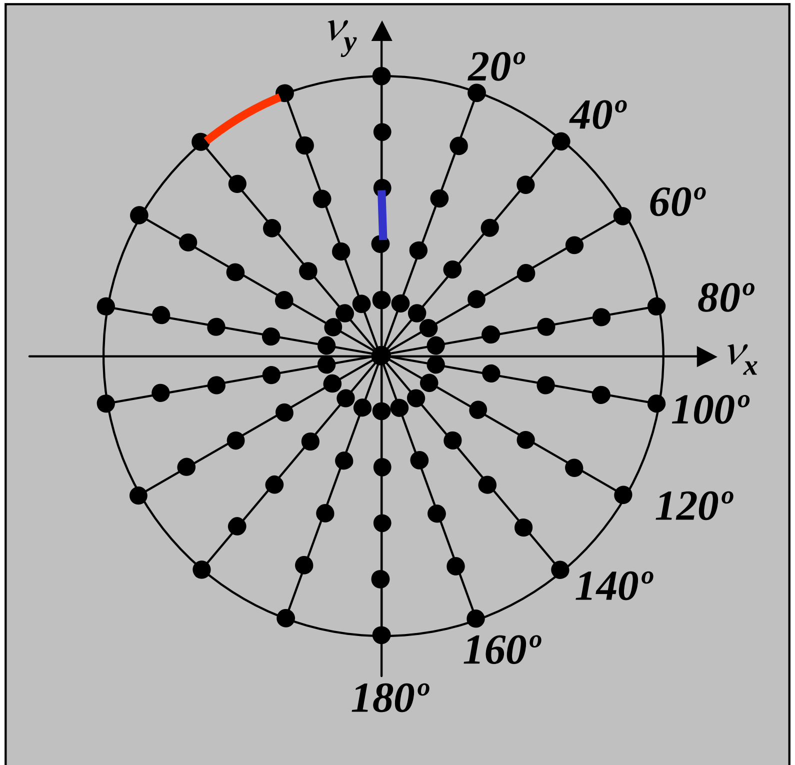


Reconstruction steps

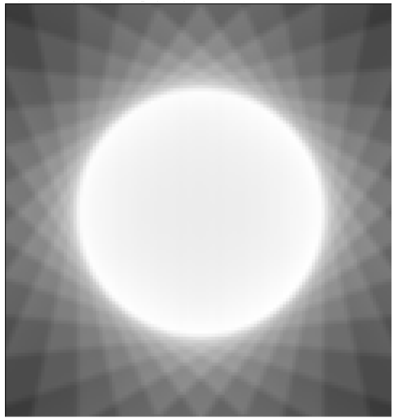


The number of projections

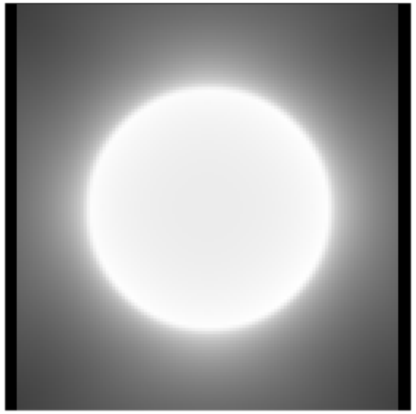
- **How to determine the number of projections per turn ?**
  - **Slice-projection theorem !**



Sampling in the Fourier domain



30 projections



1000 projections

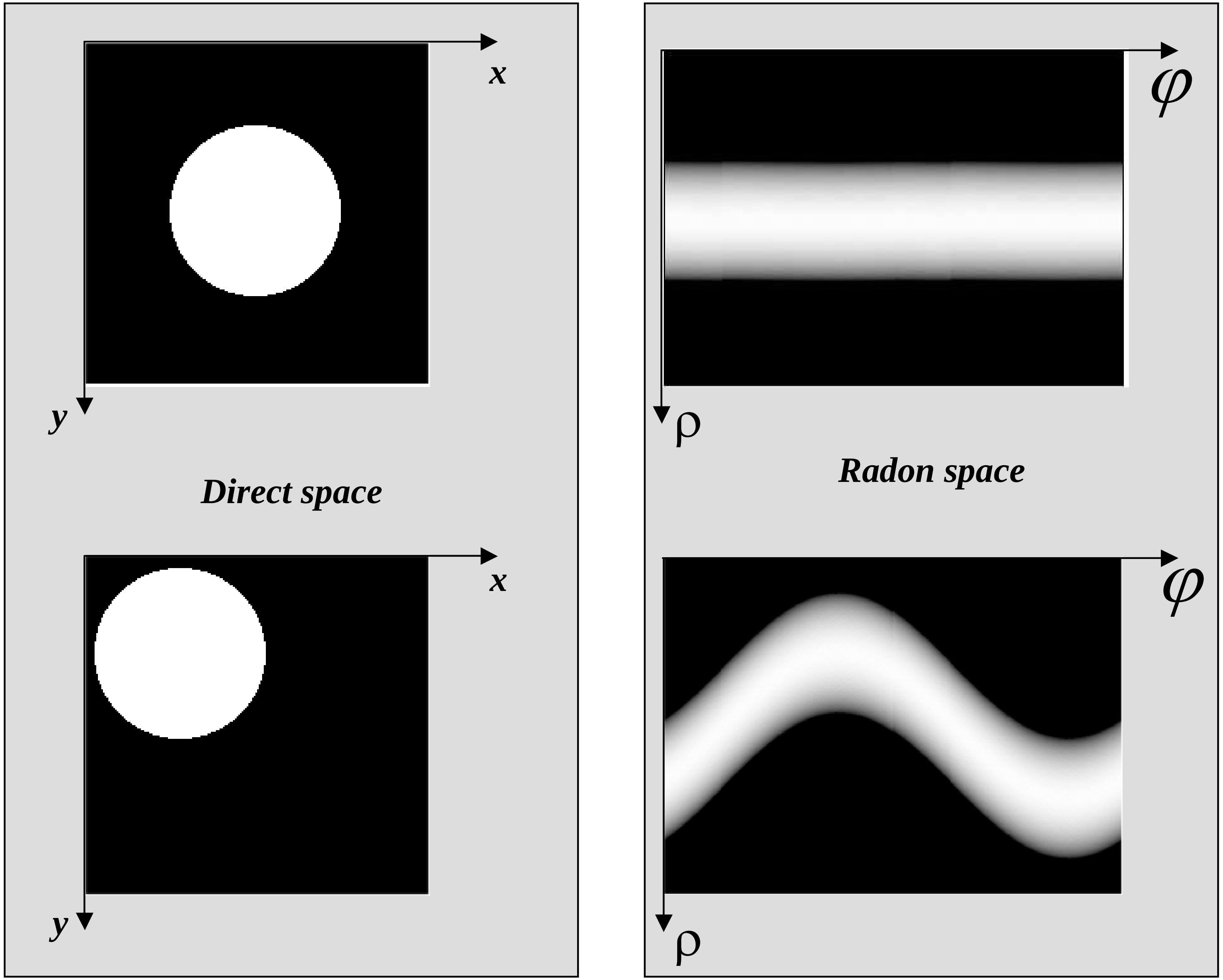
Roughly, one wants =

$$= \frac{1}{\text{Pixel\_Size} \times \text{CCD\_Size}}$$

$$= \frac{1}{2 \times \text{Pixel\_Size}} \frac{\pi}{\text{Nb\_Proj}}$$

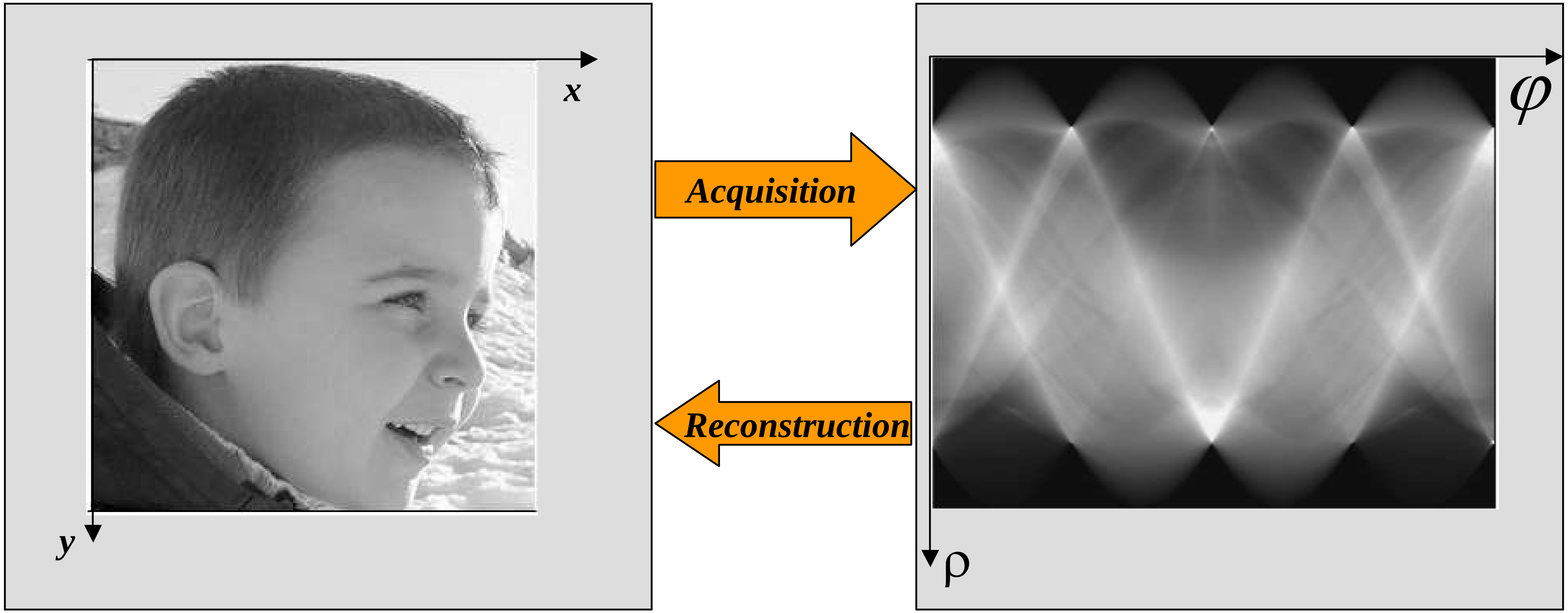
$$\text{Nb\_Proj} = \frac{\pi}{2}.\text{CCD\_Size}$$

The sinogram concept

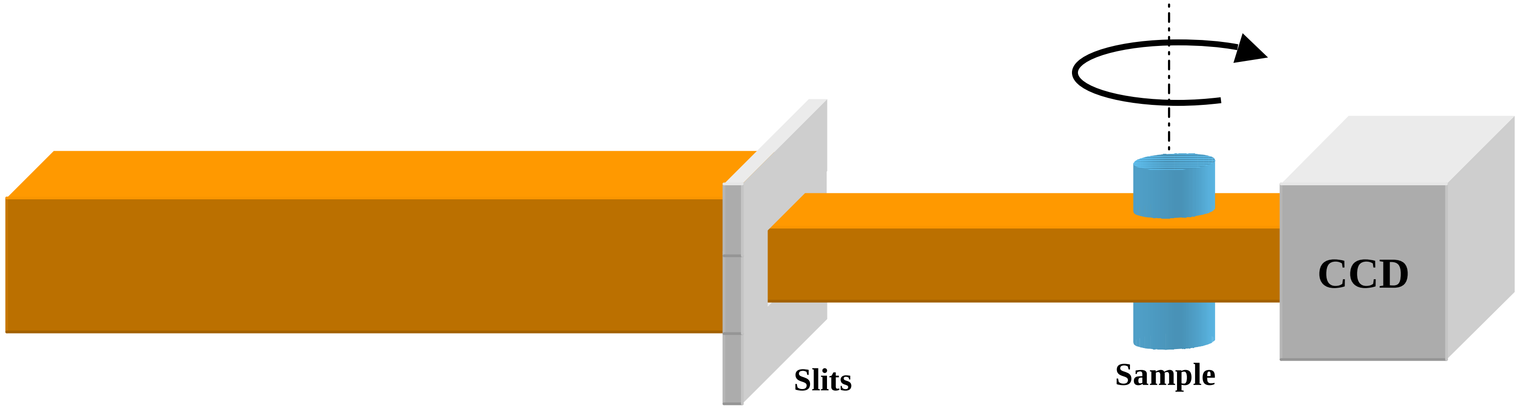


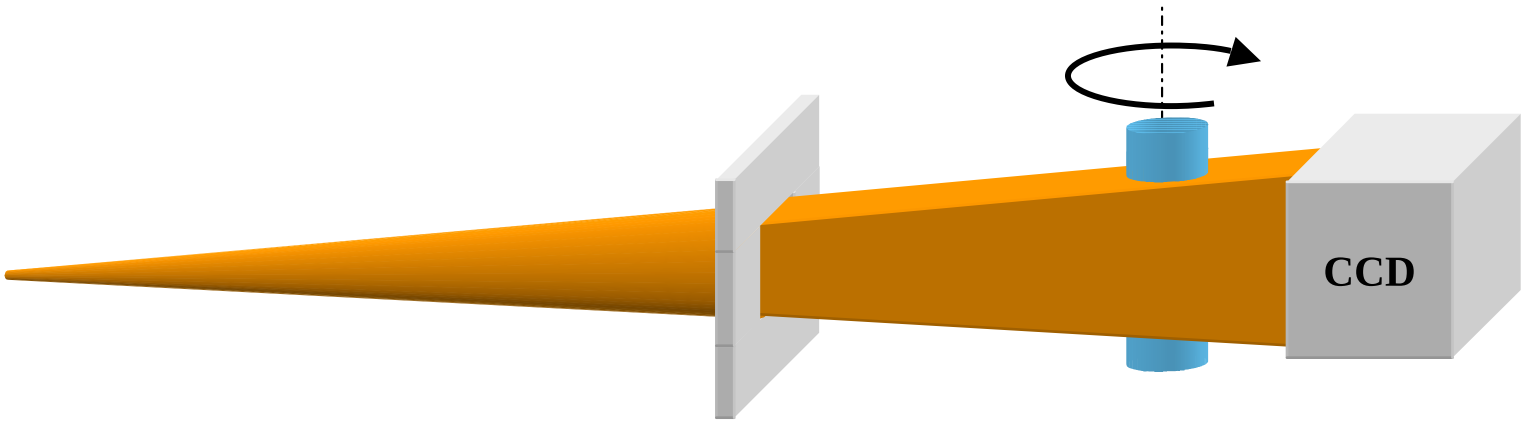
The sinogram concept

- **Sinogram = set of projections**



What about 3D ?





What about 3D ?

- **In 3D, beam shape must be taken into account**
  - **Cone beam tomography (or fan beam tomography in 2D)**

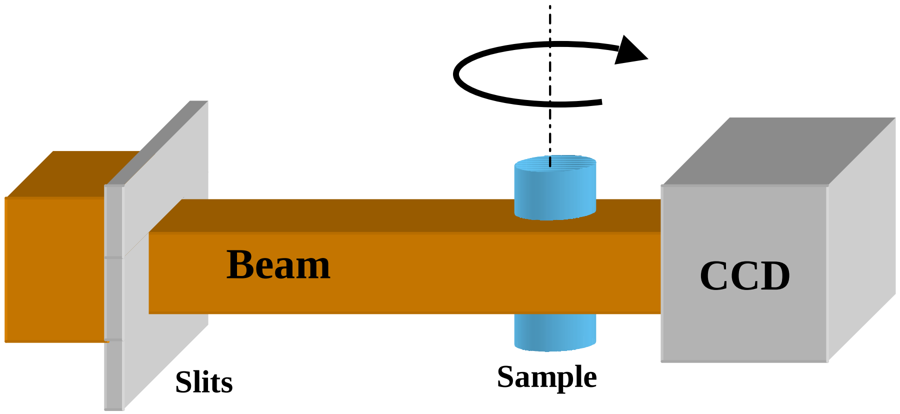
- **Advantage with synchrotron**
  - **Extremely low divergence (in comparison, divergence 30° for a tube)**
    - **Vertically : 20µrads**
    - **Horizontally 30µrads (Highβ section) or 100 µrads (Low β section)**

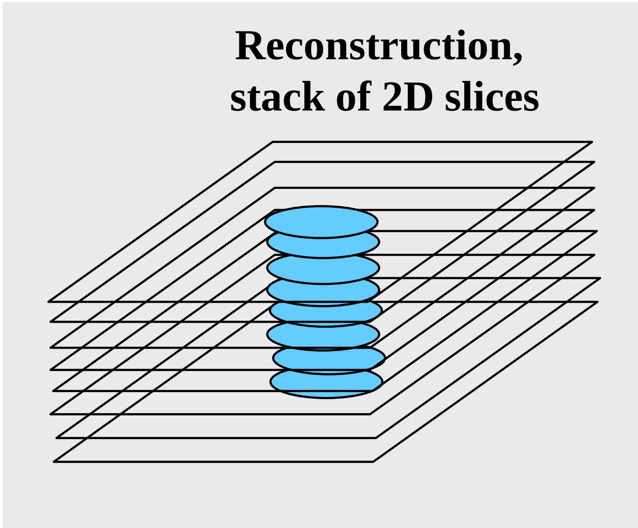
→Beam is supposed to be parallel

→ One can consider each slices separately

→ We can perform multi 2D reconstruction and not 3D

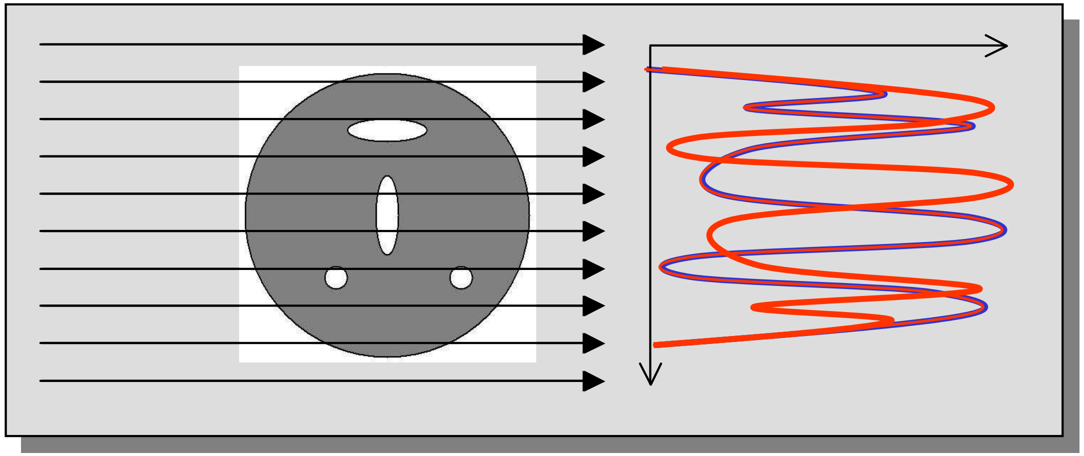
What about 3D ?





180 or 360 degrees ?

- **Fan beam → R $f(\rho, \varphi) \neq$ R $f(\rho, \varphi+180)$**
- **Parallel beam → R $f(\rho, \varphi)$ = R $f(-\rho, \varphi+180)$**

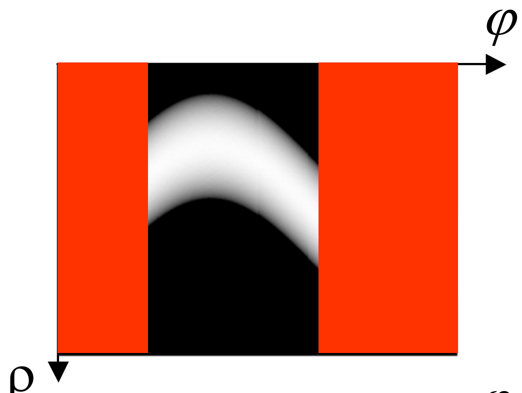


- **In parallel beam, projections at 0º and 180º are the same**

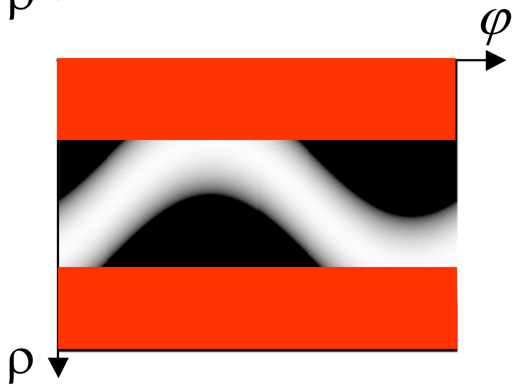
  → No need to scan over 360º, 180º is enough with a synchrotron

Incomplete data in tomography

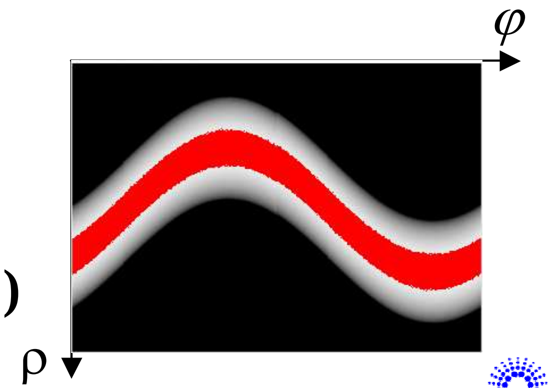
- **3 kinds of incomplete data**
  - **Limited-angle problem**
    - **Limited angular range, less than 180 degrees**
      - **Typical when using *in-situ* devices**



  - **Interior problem**
    - **Sample size > field of view**
      - **Typical when object too big/CCD too small**



  - **Exterior problem**
    - **Data not accessible locally inside the object**
      - **Typical when**



- **Algorithmic solution or approximation**
  - **Iterative algorithms (ART, SART, MART, SIRT,…)**

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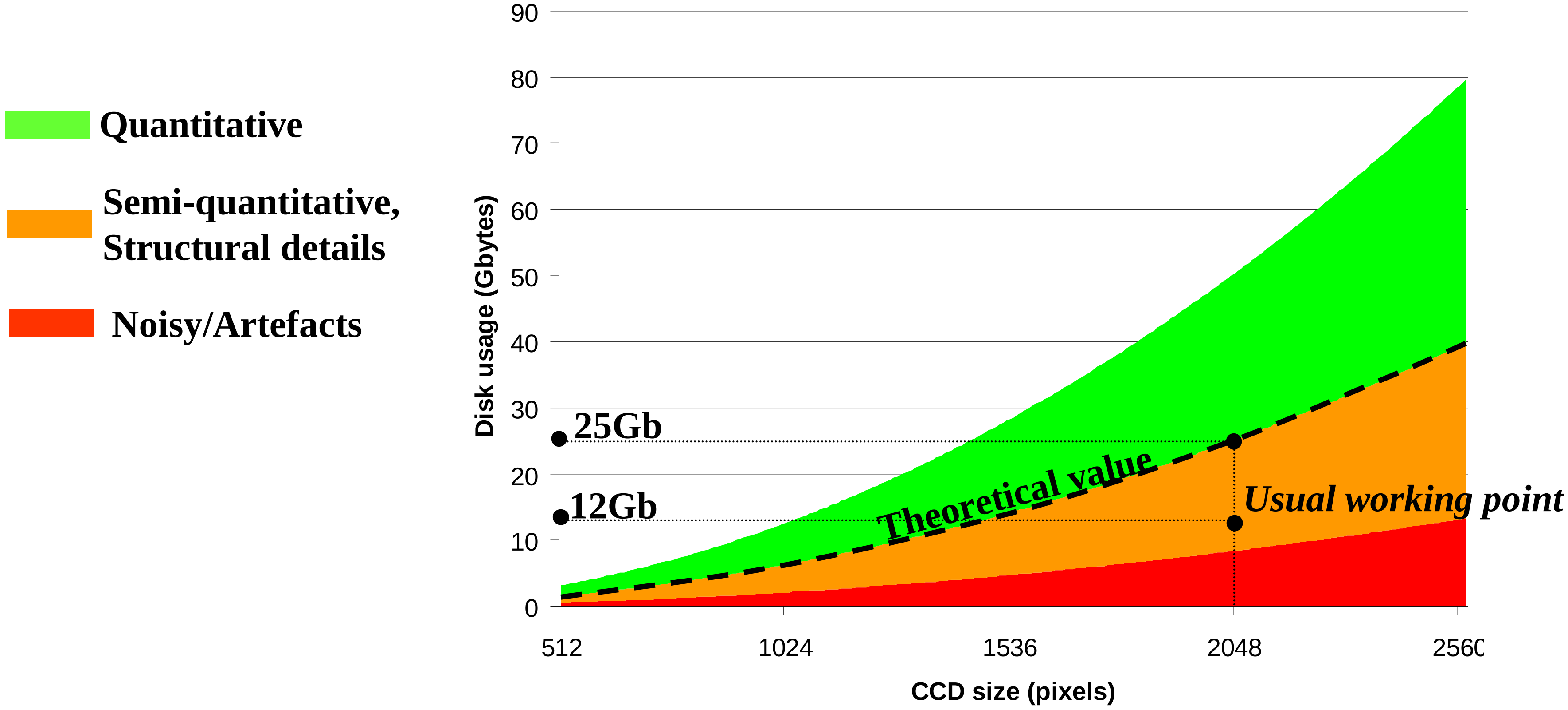
The number of projections

- **Theoretical number of projections : π/2×CCD_size**
  - **Example : Frelon 2000→~3000 projections**



Compromise size/resolution

- **Users often want to image big objects at high resolution**
  - **The beamline setup should be adapted accordingly**
- **However : practical limitations**
  - **Beam size is limited→ local tomography or stitching**
  - **Computing issues**
  - **Does it make sense ?**

Local tomography

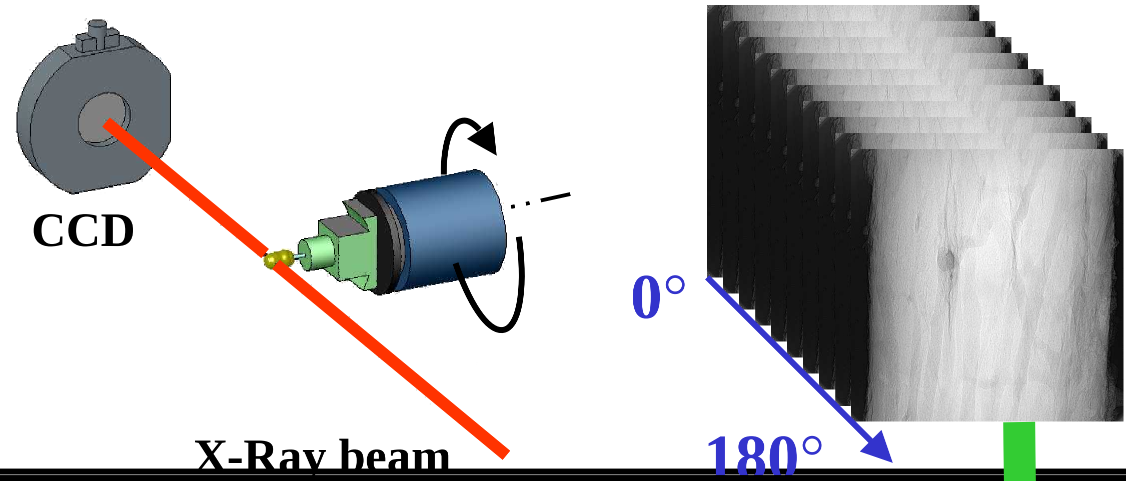
- **Condition for good reconstruction**
  - **Sample size < field of view for any angle**
  - **Example : Frelon 2000, 0.7µm pixel size**
    - **Field of view = 2000 ×0.7=1.4mm →Sample cross section< 1.4mm**

- **Problem could be avoided by using stitching**
  - **Example : Object 10cm cross section, height 10cm , 0.7 µm pixel size**
    - **Size of the reconstructed object**
      - **10^{15} voxels = 1 PetaByte (1000 TeraBytes or 1.000.000GigaBytes) in 8bits = 250.000 DVDs**

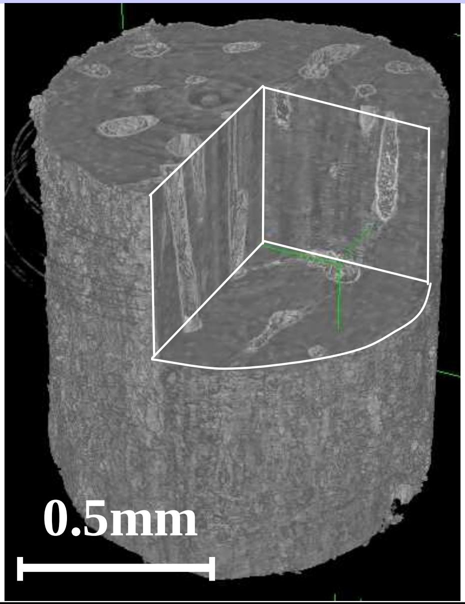
- **Also the setup must be adapted to the scientific need, one has to keep reasonable…**

Tomography

1. Acquisition



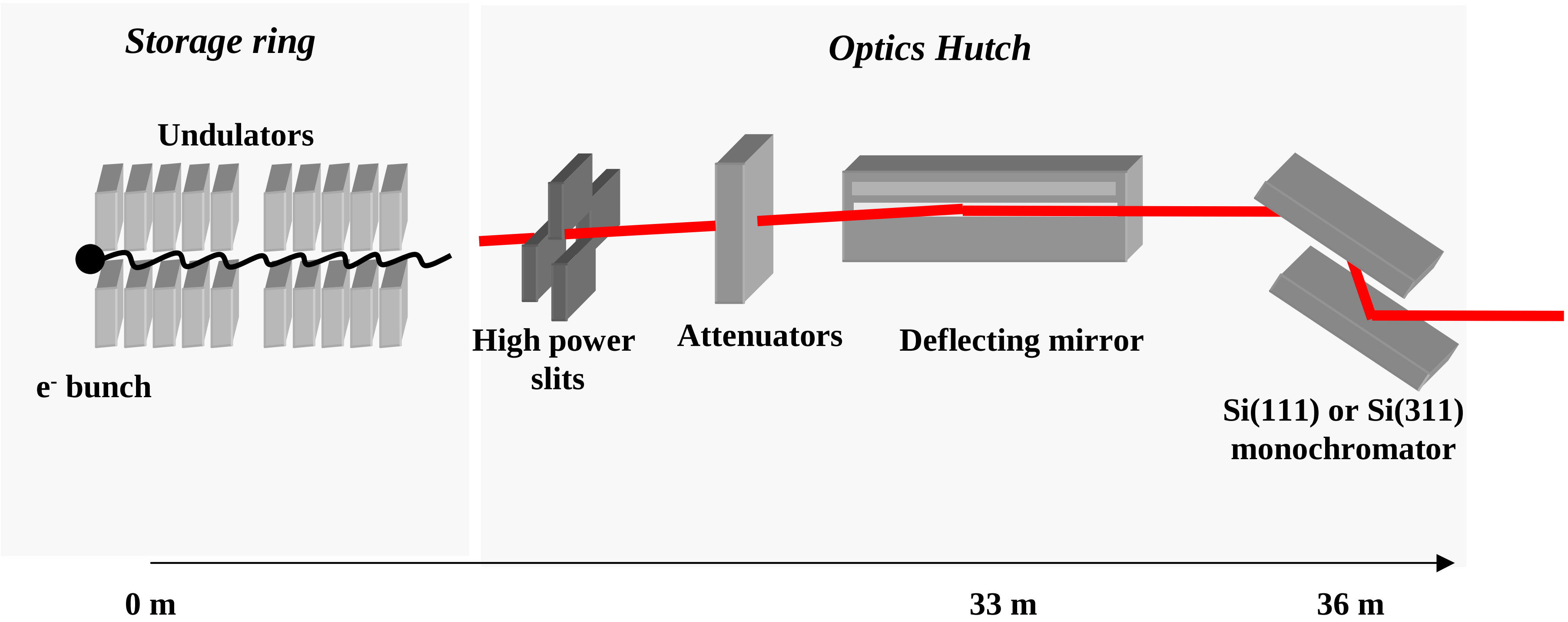
2. Reconstruction



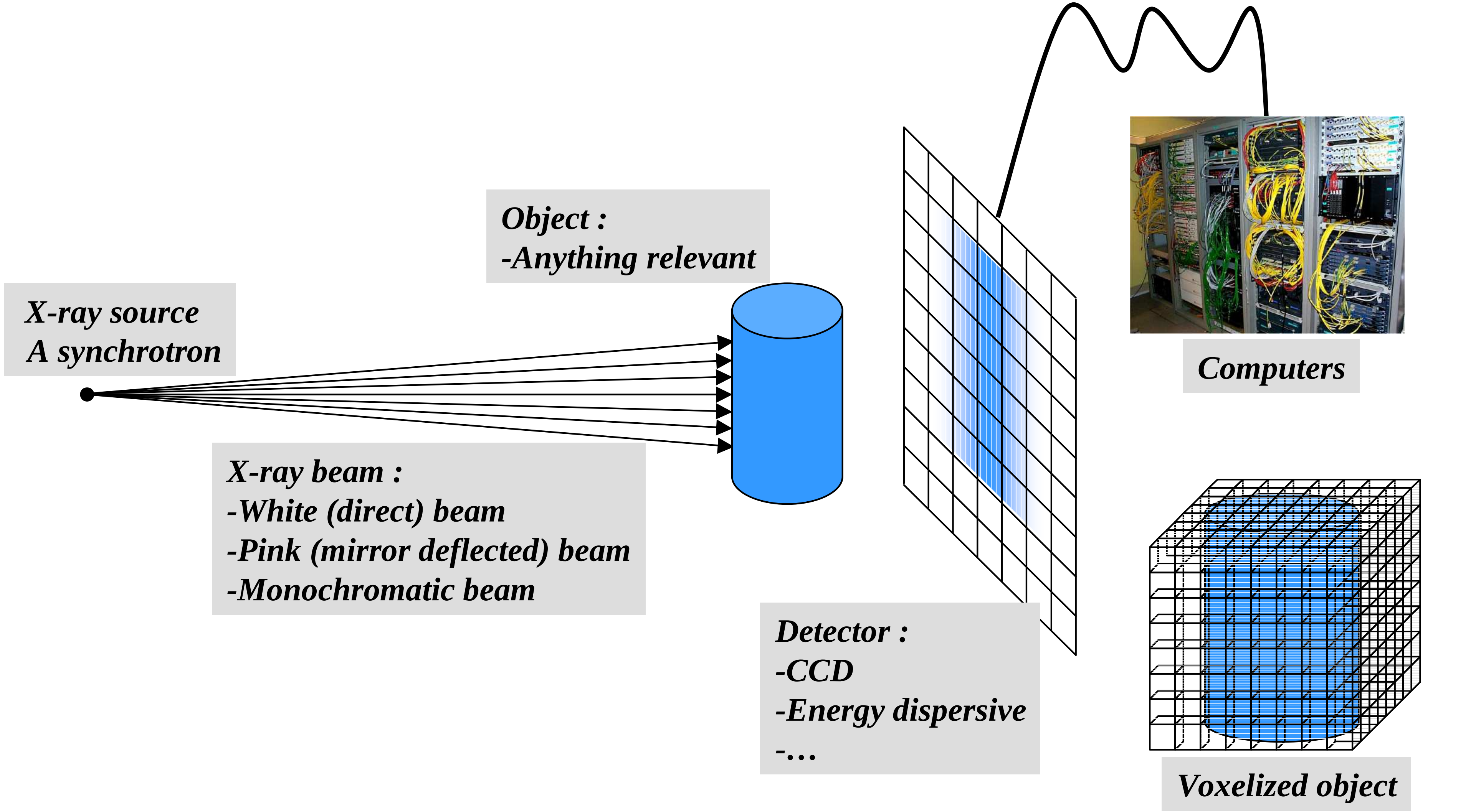
Filtered backprojection

3D volume

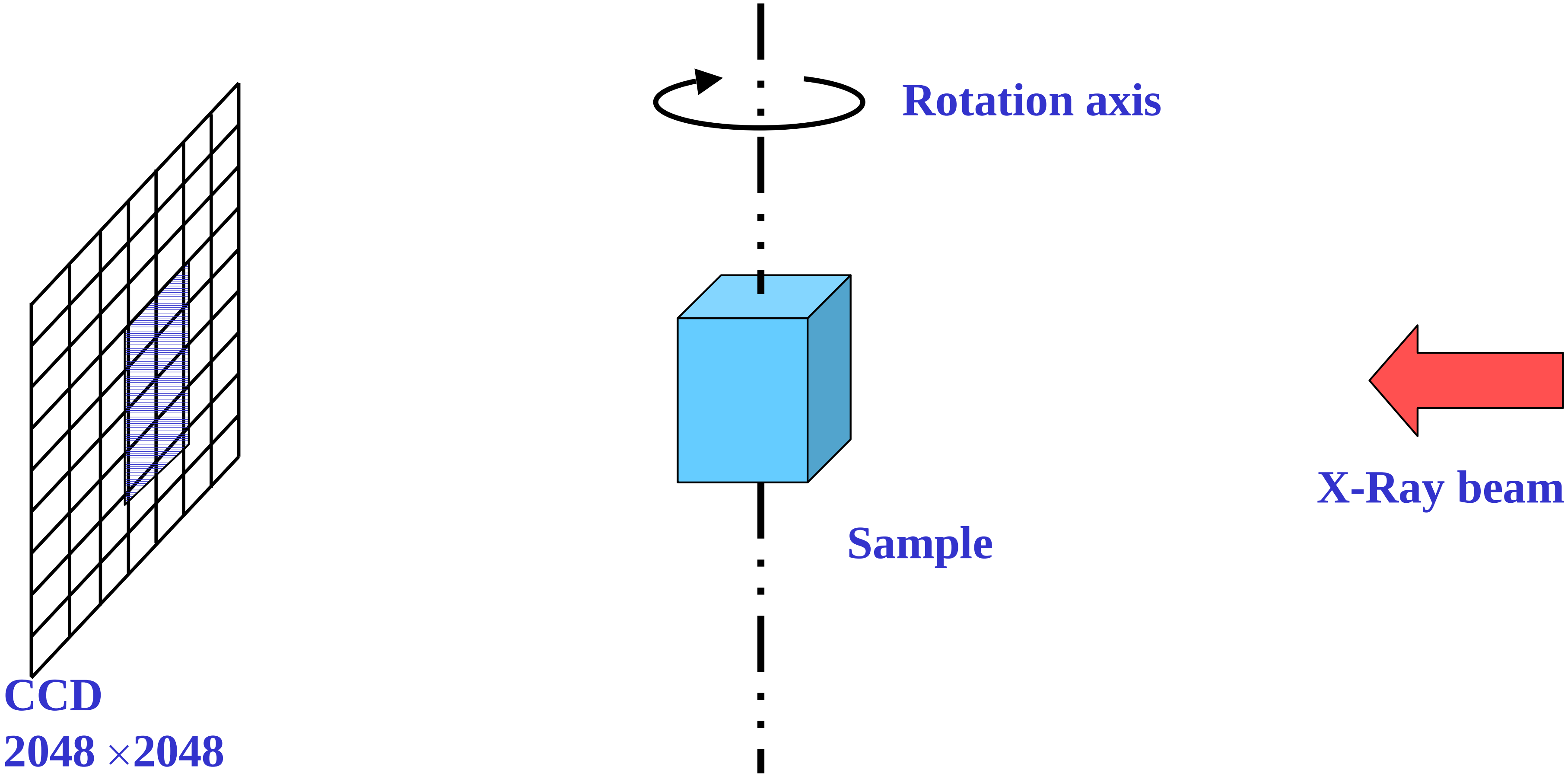
A beamline layout



A basic beamline layout for absorption imaging

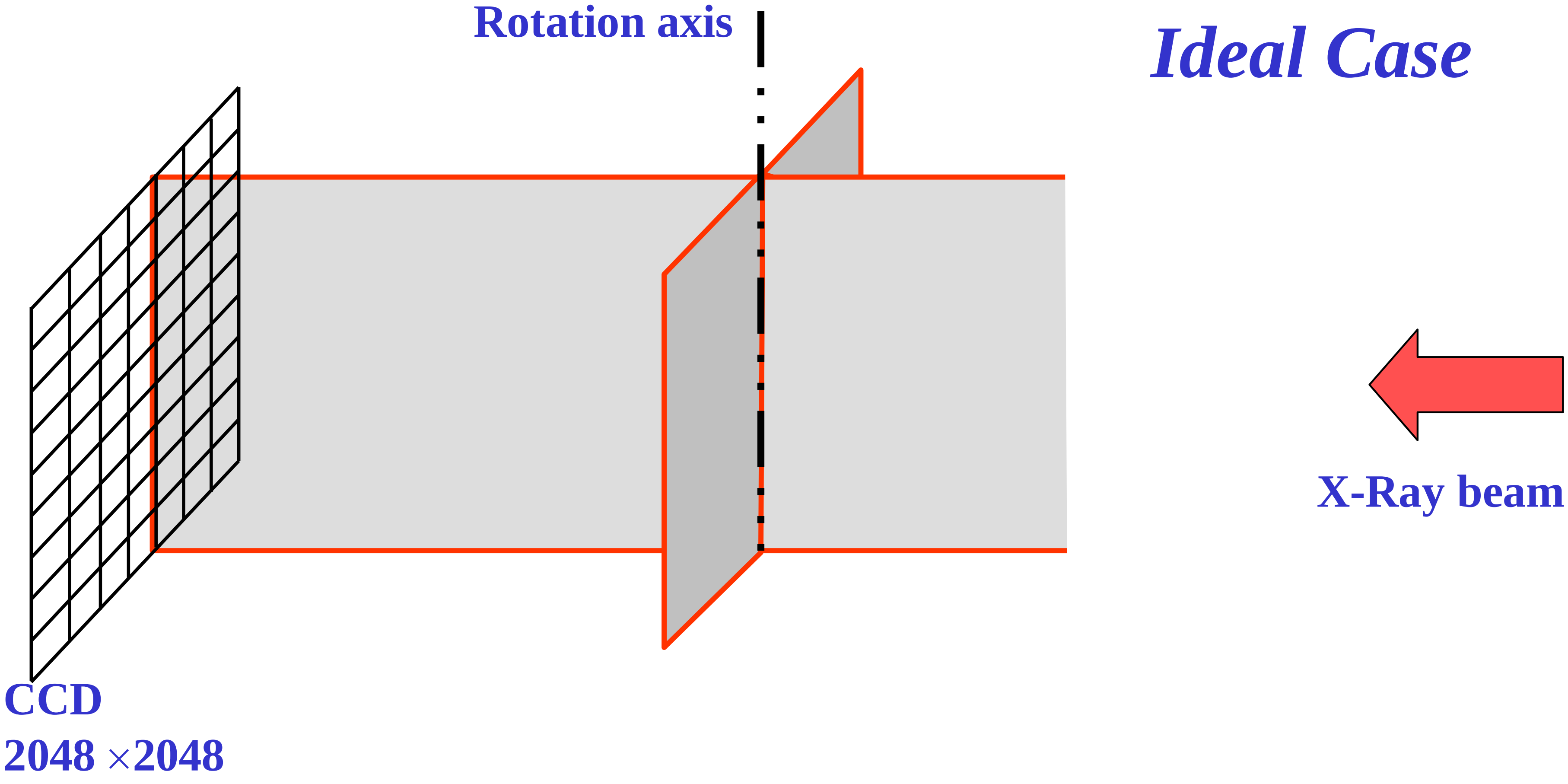


Absorption tomography acquisition



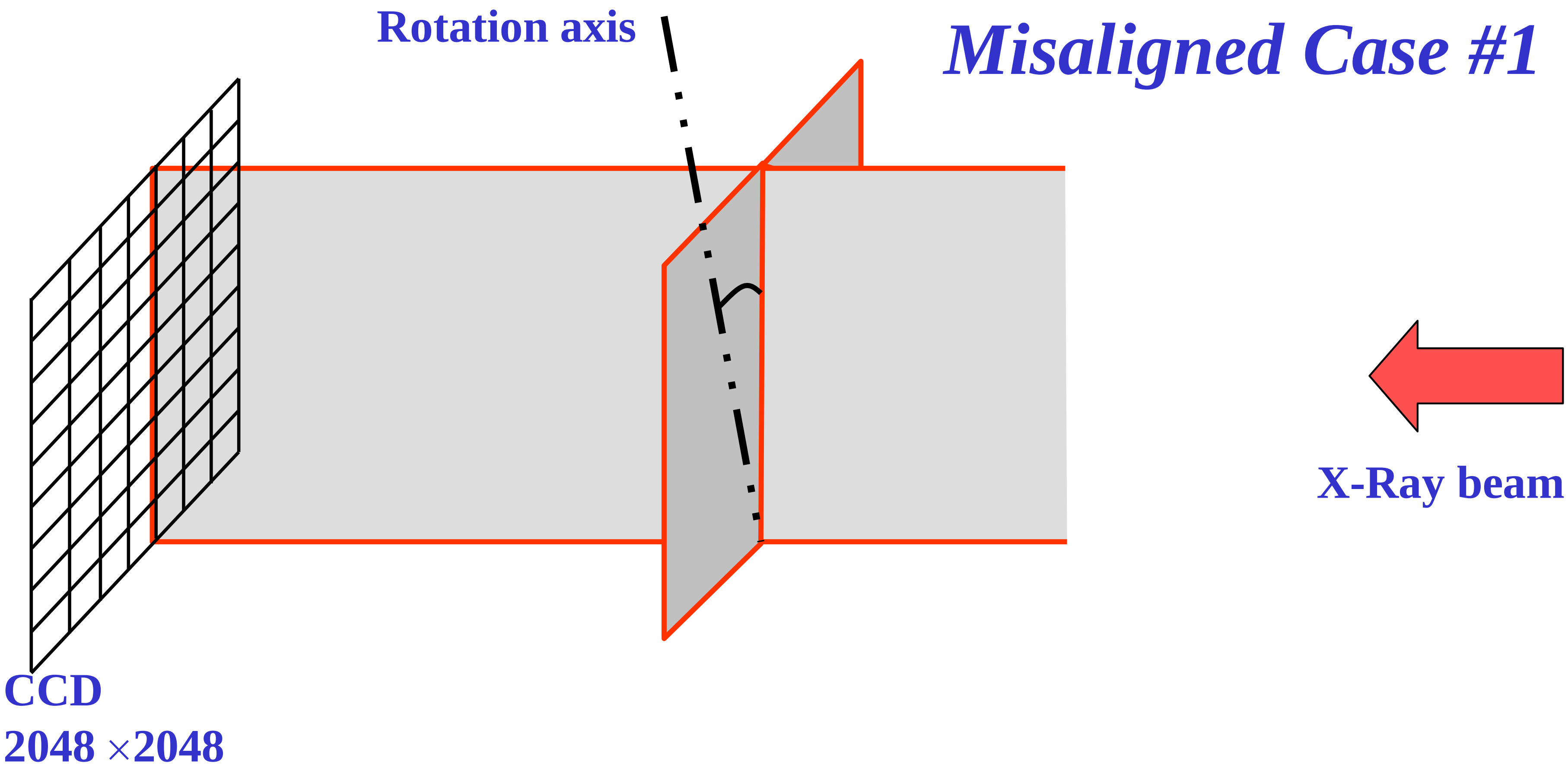
⇒Set of 1000 projections over [0,180]degrees

Geometrical calibration

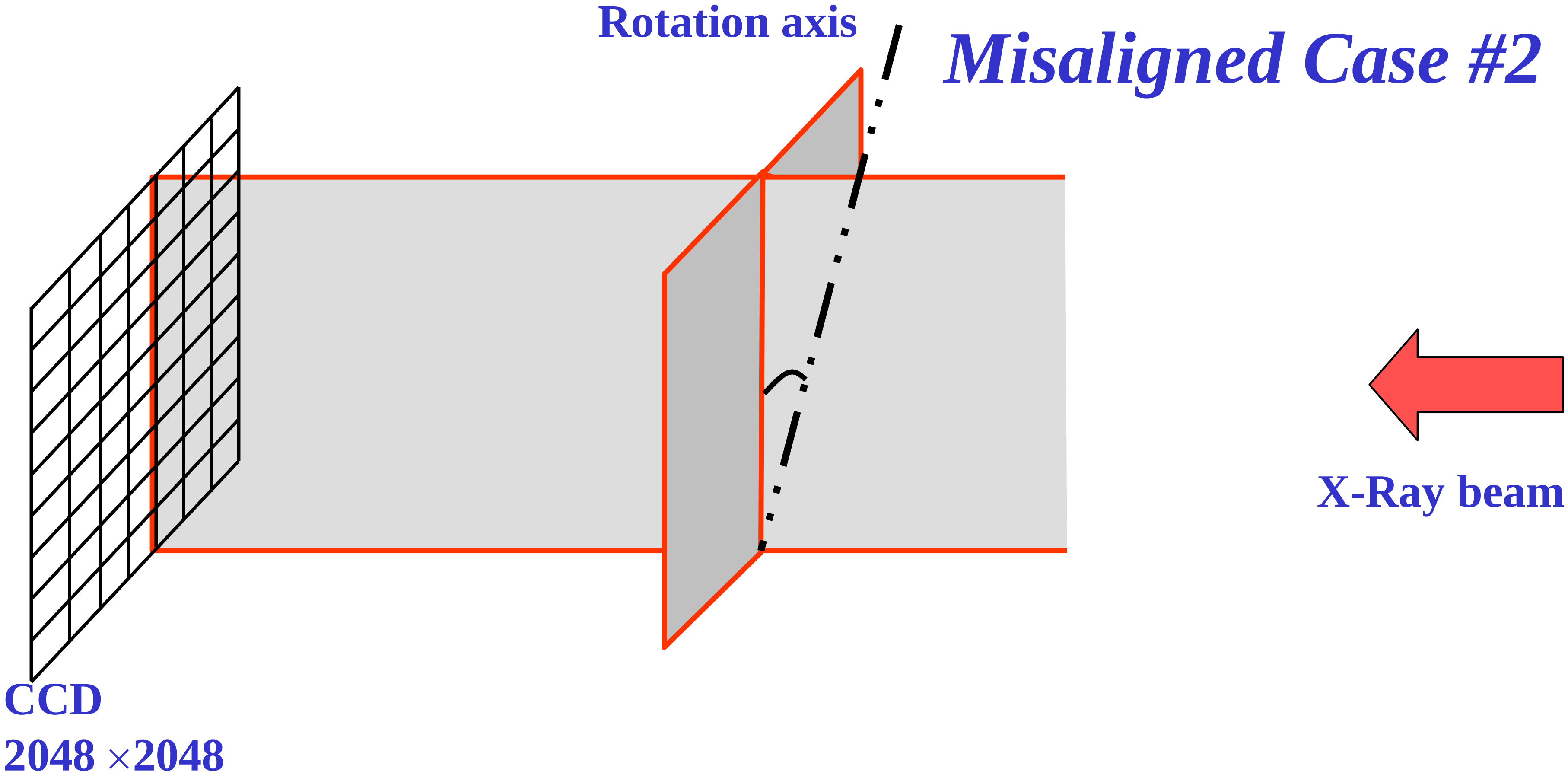


Geometrical calibration

Misaligned Case #1

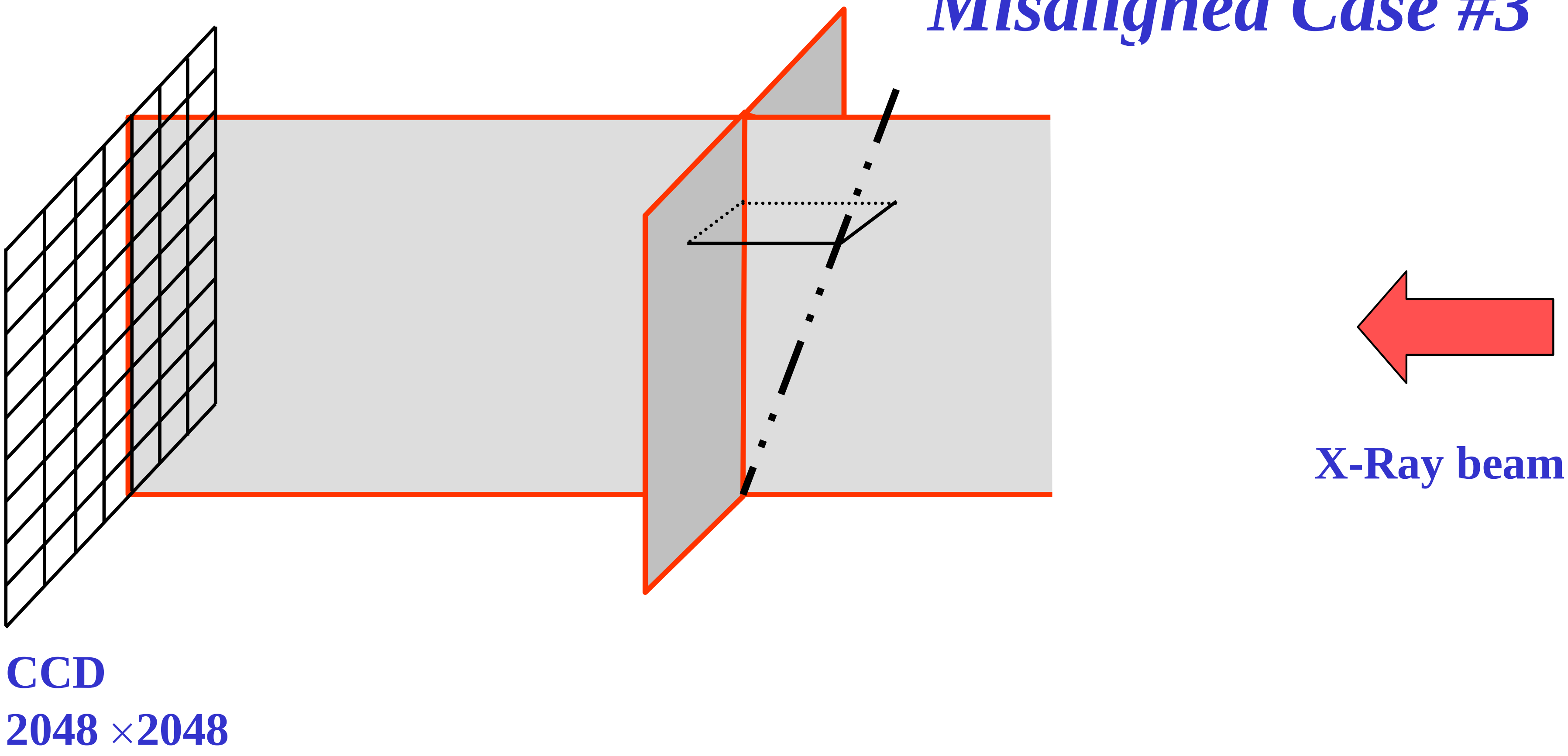


Geometrical calibration



Geometrical calibration

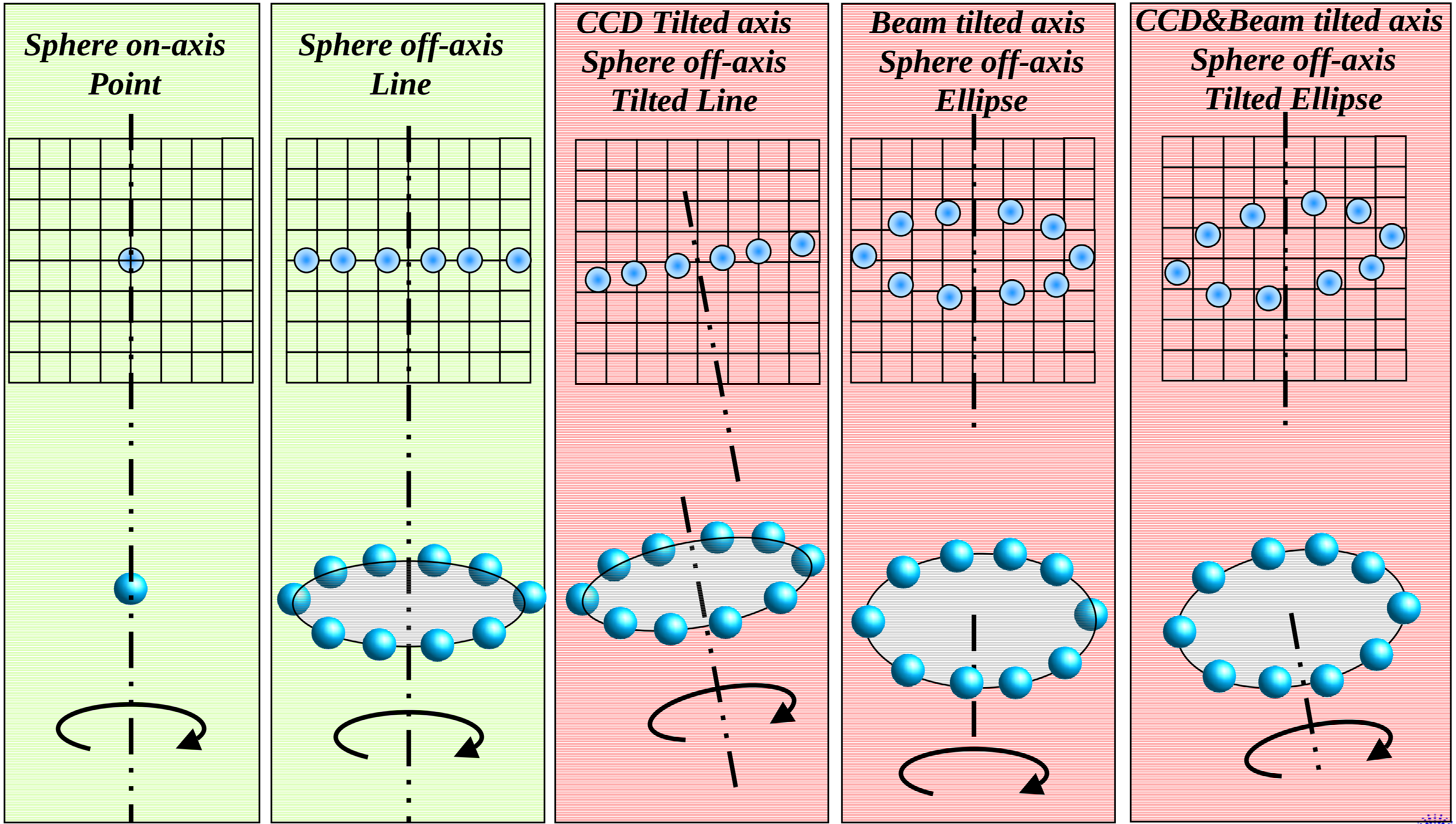
Misaligned Case #3



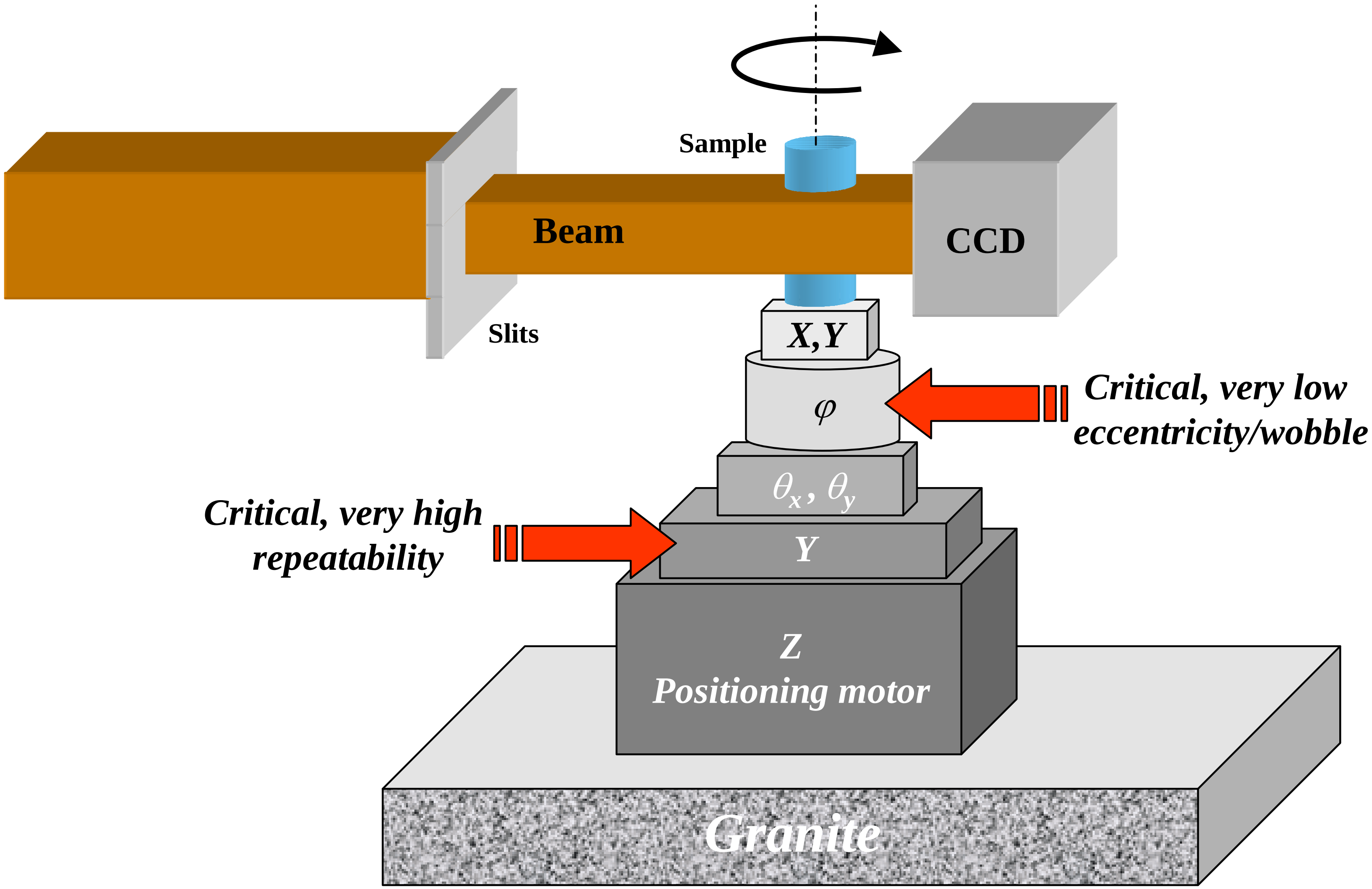
Standard methods

- **Basic idea**
  - **Use of fiducial markers**
    - **Wires**
    - **Small spheres + Center of mass**
    - **Position at 0 and 180 degrees→Measure the angles**

Misalignment artifacts

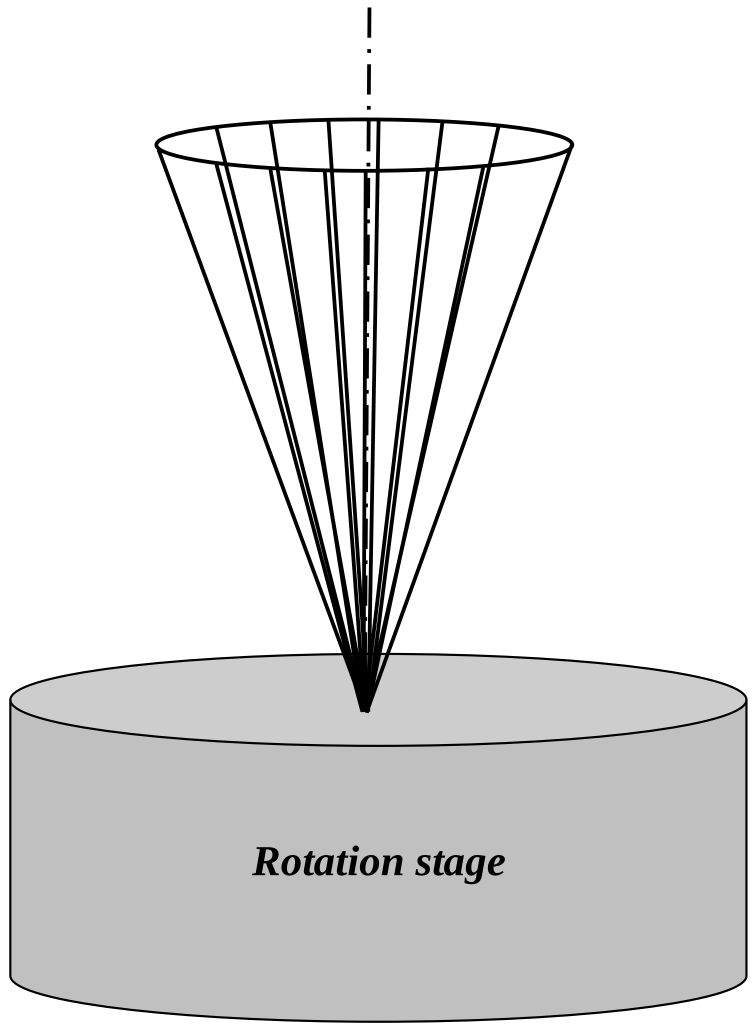


The basic of mechanics for absorption micro-tomography

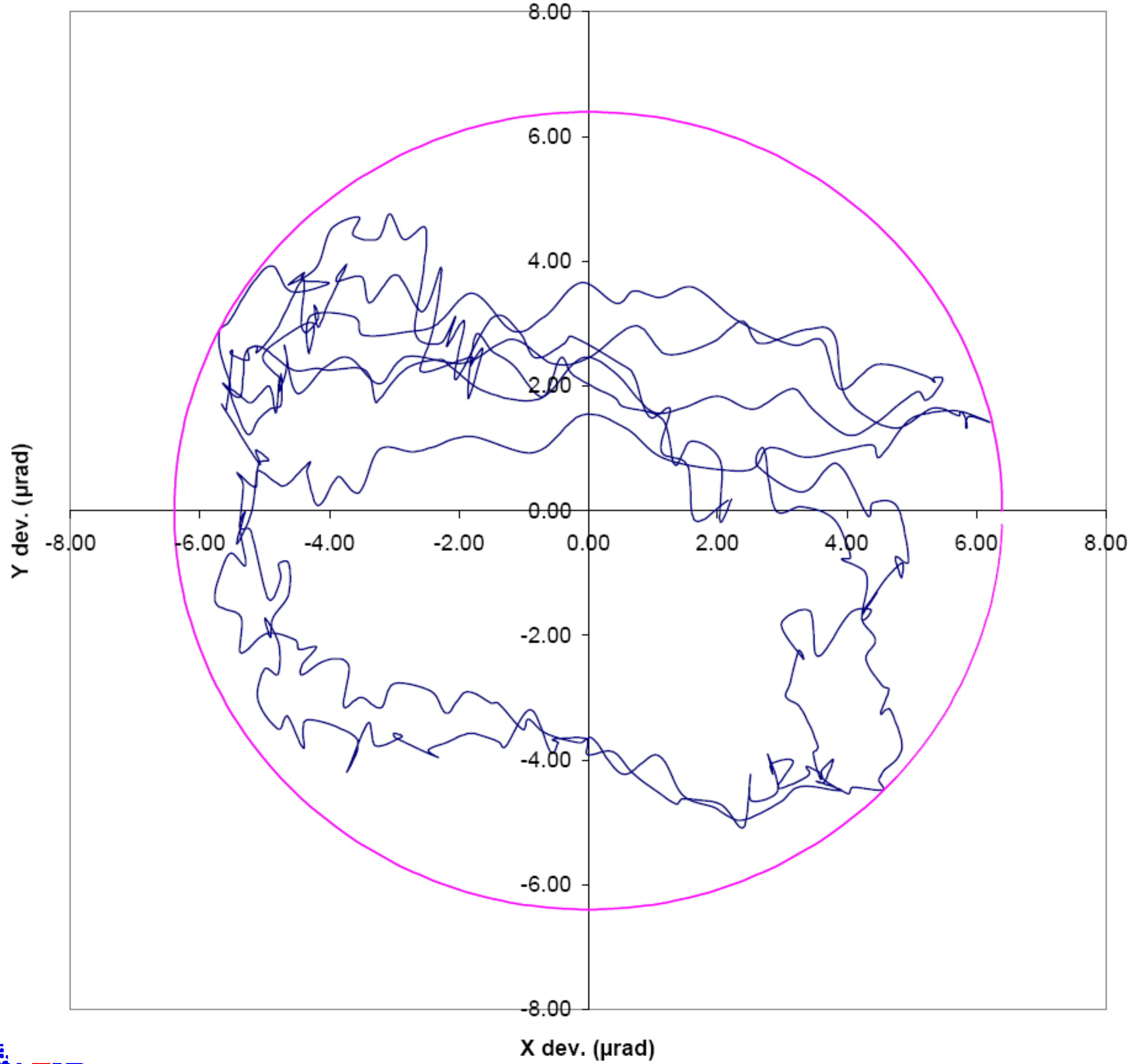


The rotation motor

- **Main parameters**
  - **Wobble**
  - **Eccentricity**
  - **Angular resolution**
  - **Compactness**
  - **Speed**



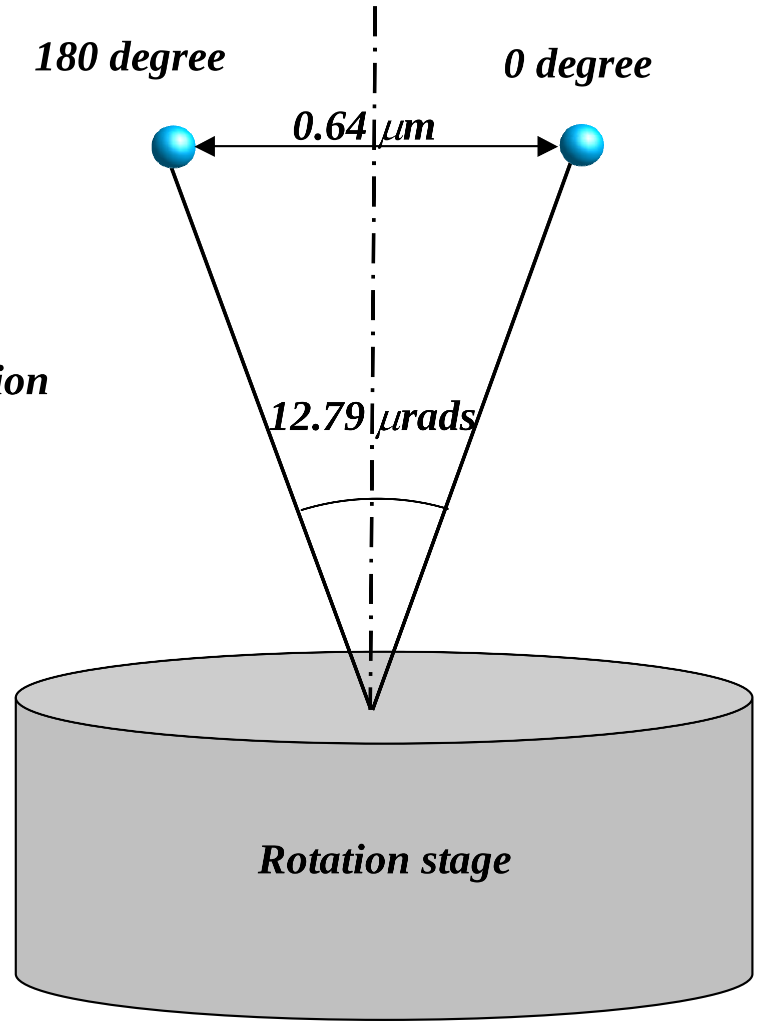
Some real wobble measurment



Total angle 12.79 µrads

Measured by
M. Nicola
H.P. Van der Kleij
Precision Engineering Lab, ESRF

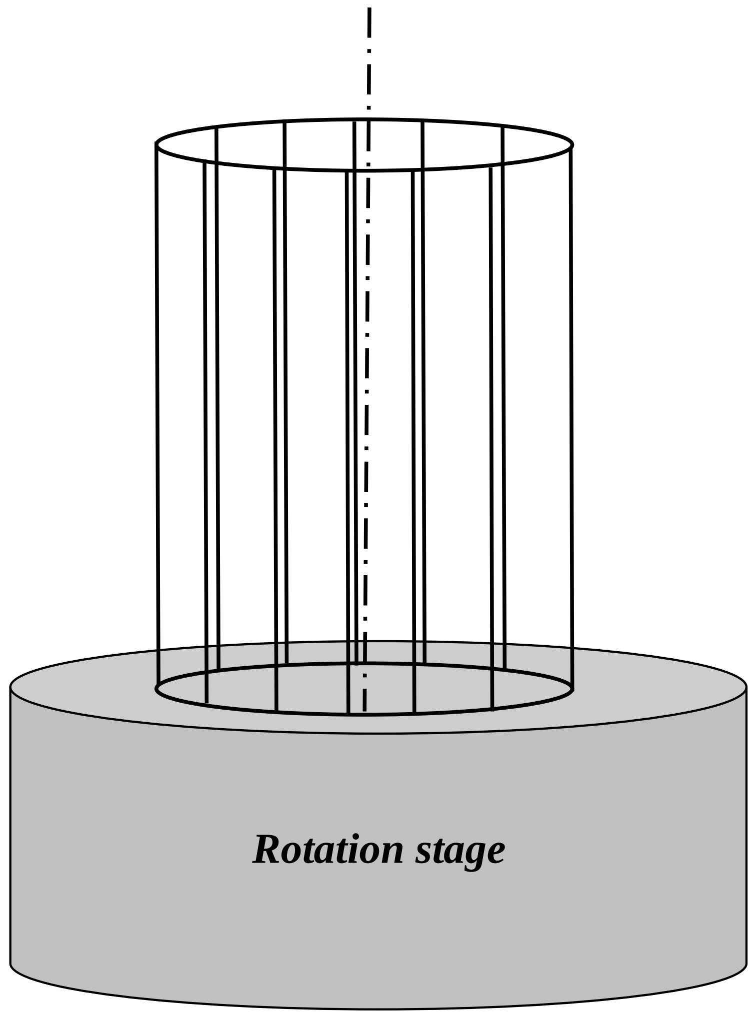
The wobble effect



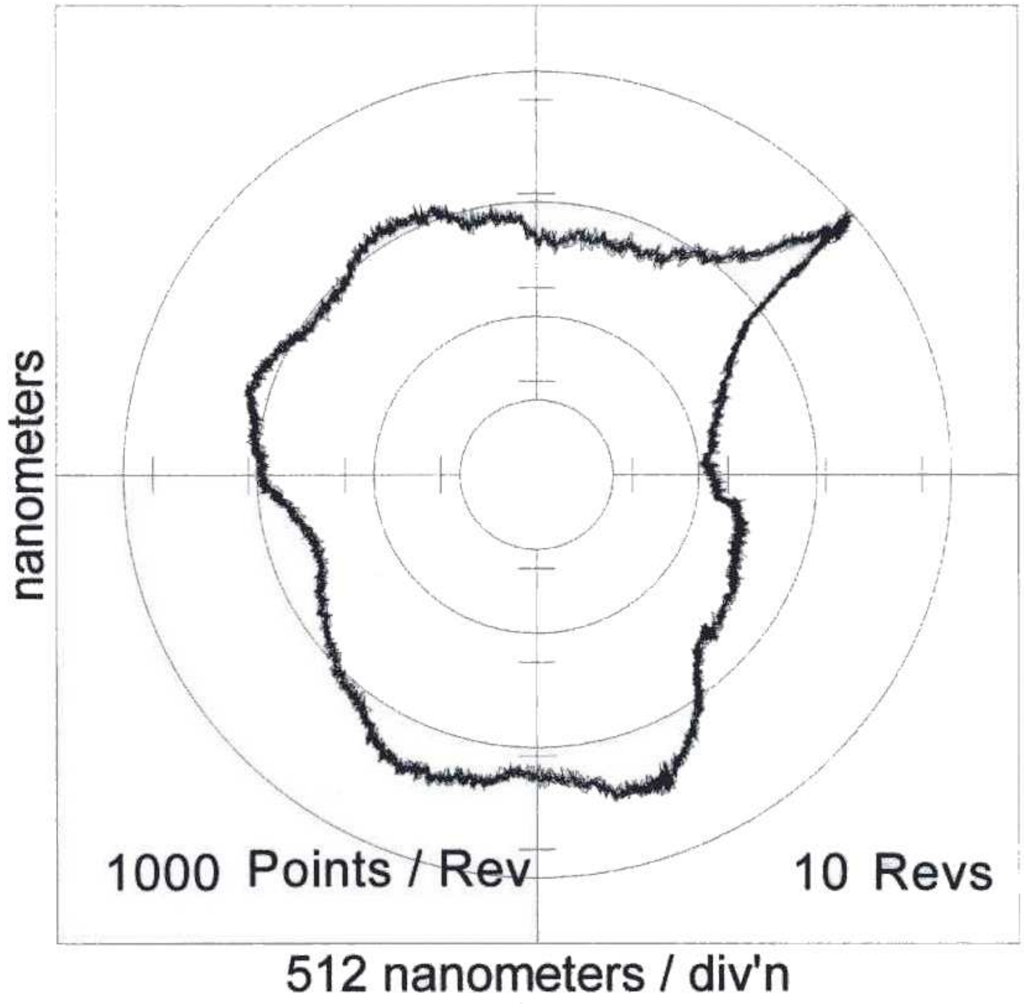
Sample 5cm from the rotation
→0.64 microns motion

The rotation motor

- **Main parameters**
  - Wobble
  - Eccentricity
  - Angular resolution
  - Compactness
  - Speed



Some real eccentricity measurement



Total motion: 5.51 μm

Measured by
M. Nicola
H.P. Van der Kleij
Precision Engineering Lab, ESRF

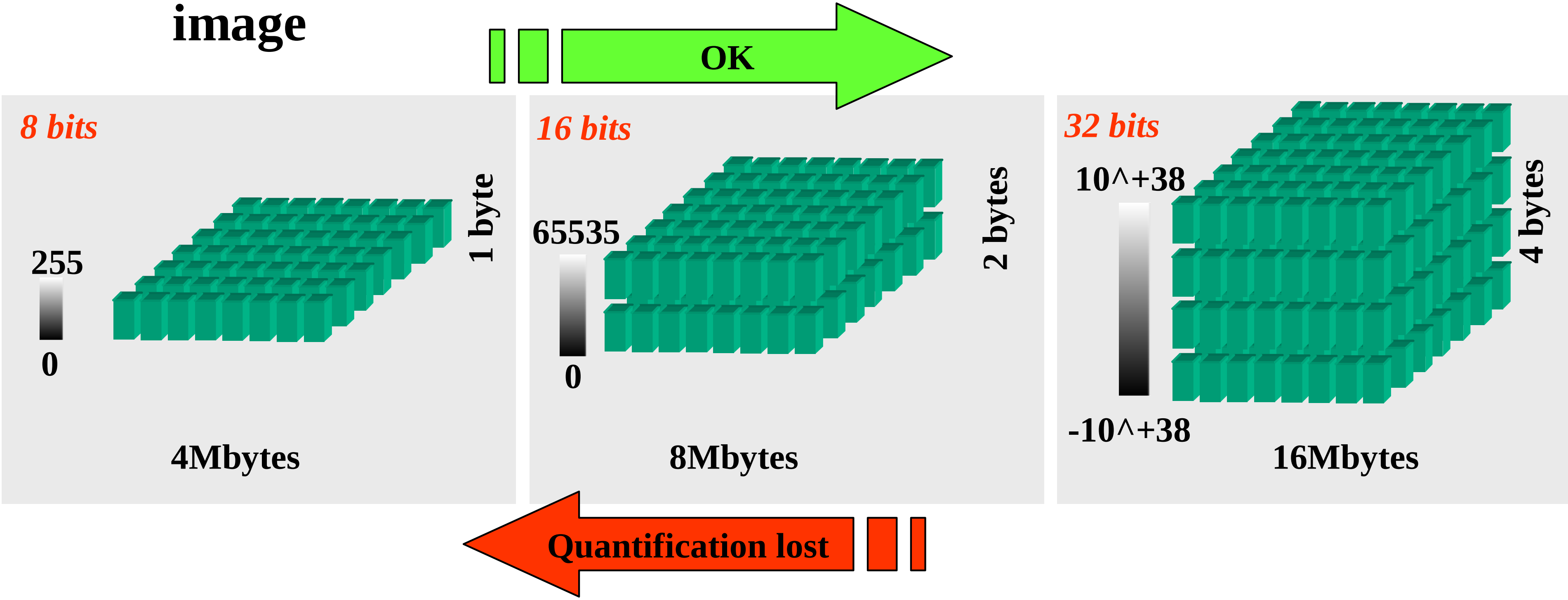
Rotation and resolution

- **The quality of the rotation depends on the required resolution**
  - **A point on-axis must ideally remain in a pixel**

→(Eccentricity + Shift _wobble) < pixel size

Image coding

- **Reconstruction**
  - **Fourier transforms, interpolations→floating point 32 bits image**



The byte order problem…

- **Example**
  - **4 bytes positive integer coding**

• Low Byte First or Little Endian representation

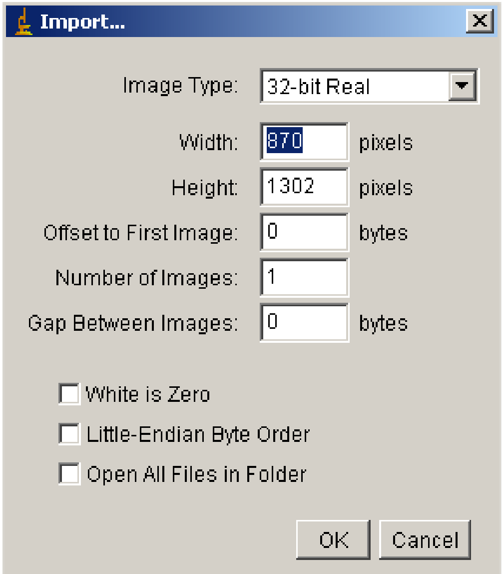
Byte #3	Byte #2	Byte #1	Byte #0	
1 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	$= 2^{31}-1 = 2.147.483.647$

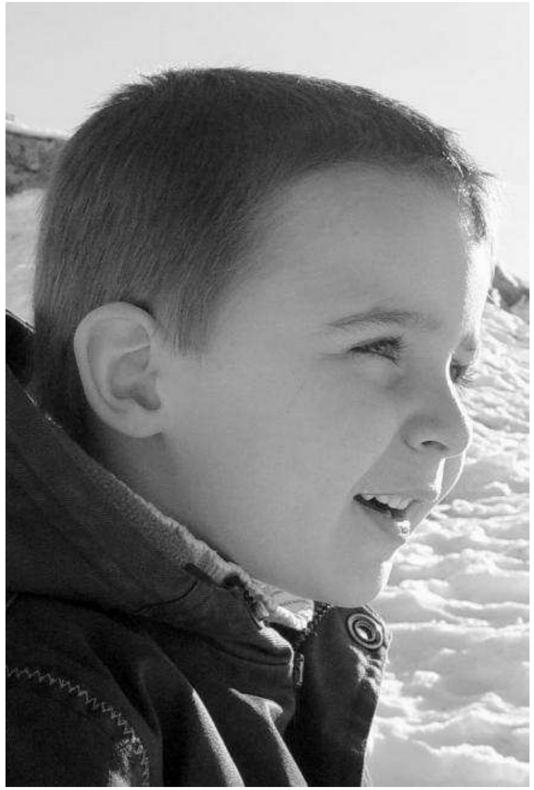
• High Byte First or Big Endian representation

Byte #0	Byte #1	Byte #2	Byte #3	
1 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	$= 2^{7}-1 = 127$

- **Remember**
  - **Intel processors (PC's) →Little Endian order**
  - **Motorola, UltraSPARC processor (MAC, SUN) →Big Endian Order**

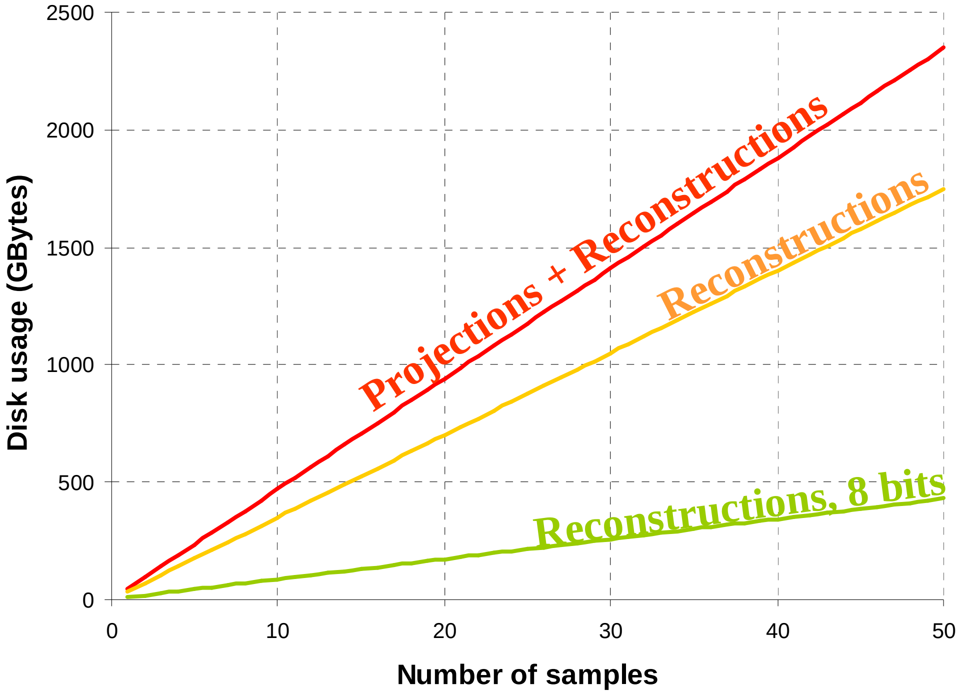
The byte order problem…

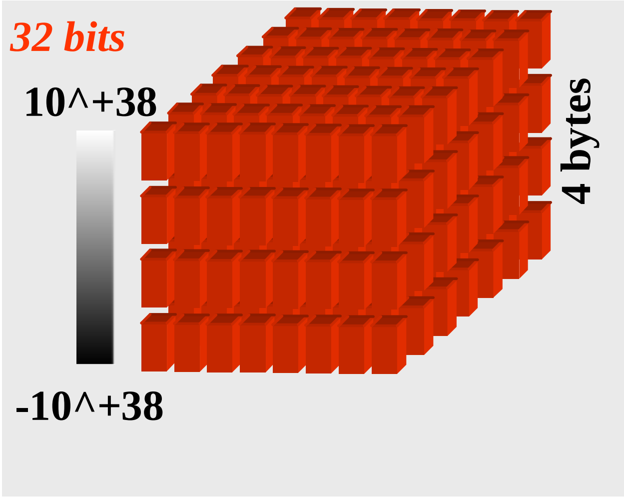


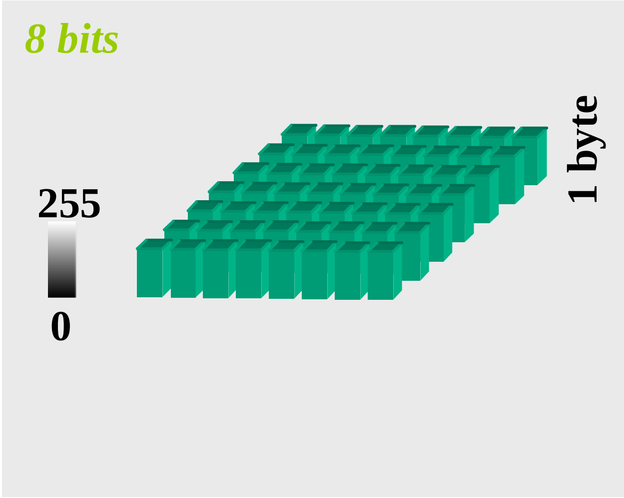


- **Warning !**
  - **By default with ImageJ, binary images are saved in Big Endian order, even on Windows PC….**

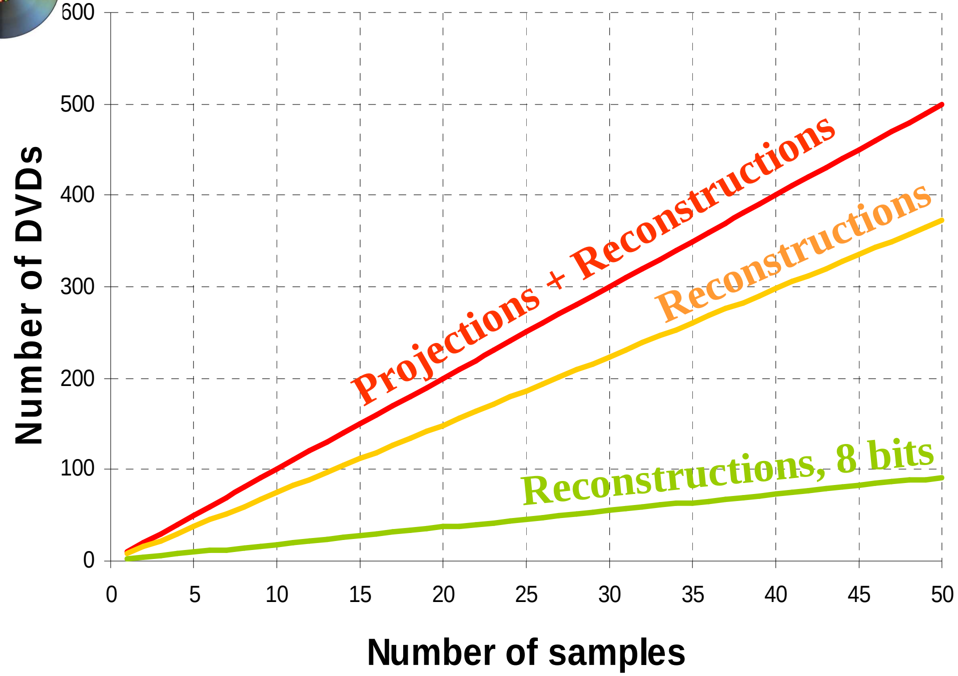
Computing considerations

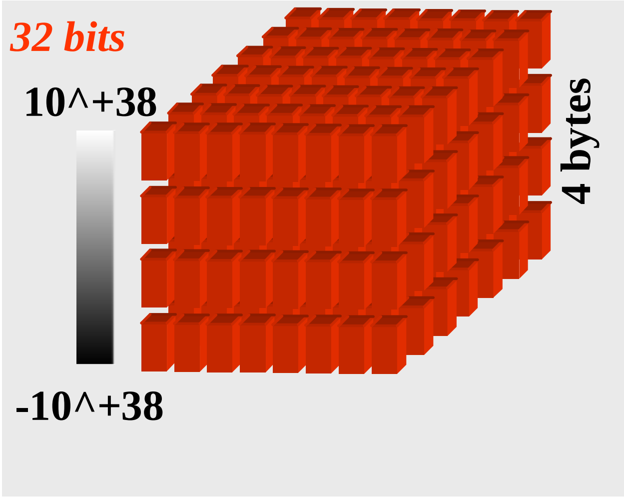


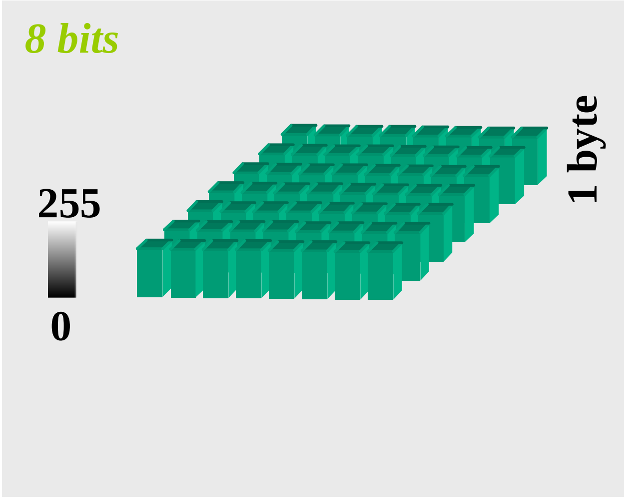




Computing considerations







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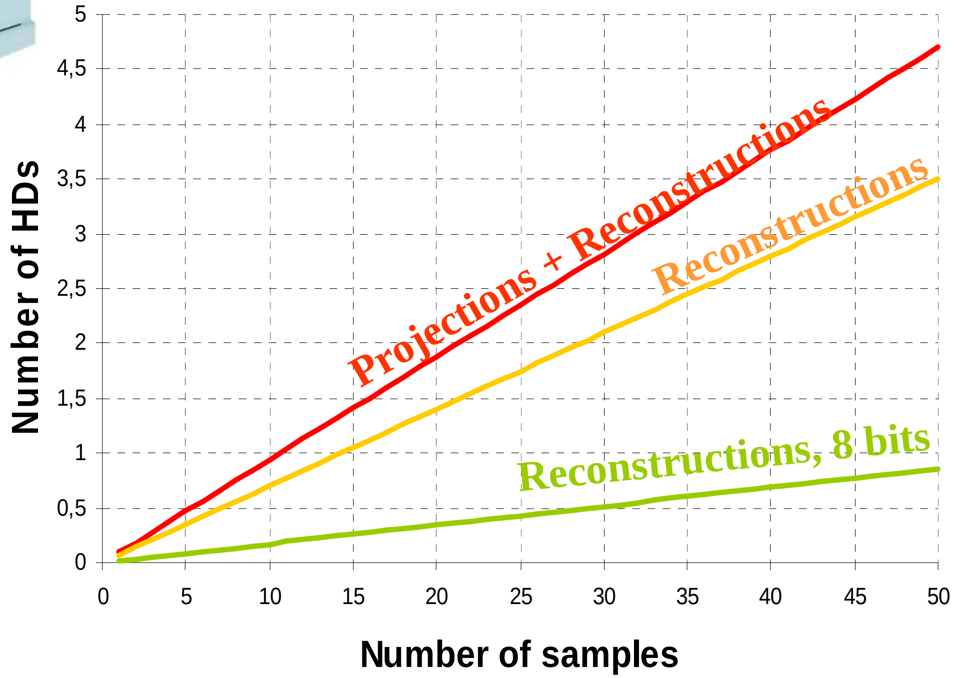
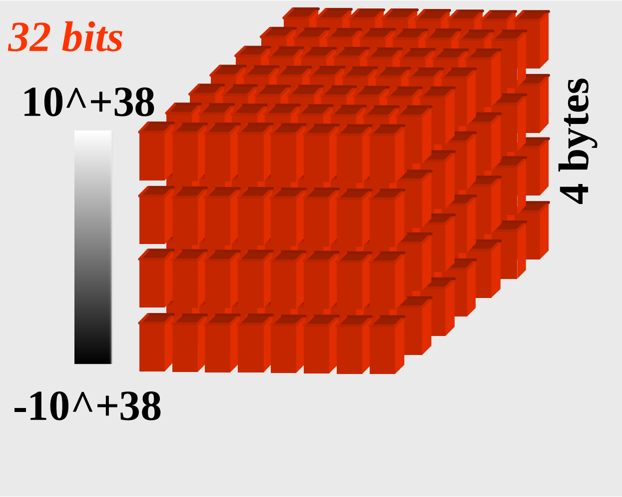
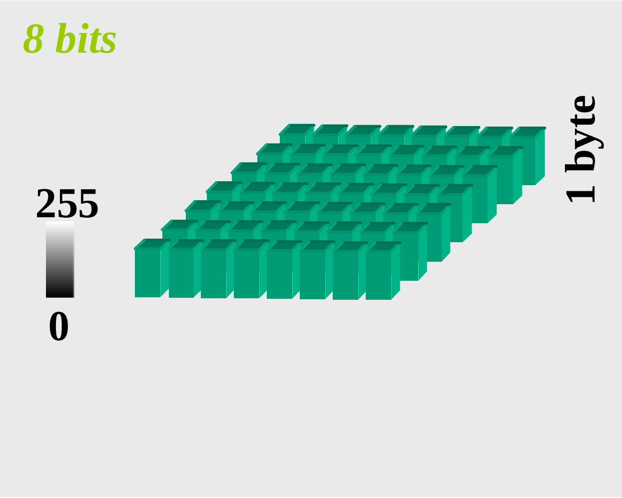
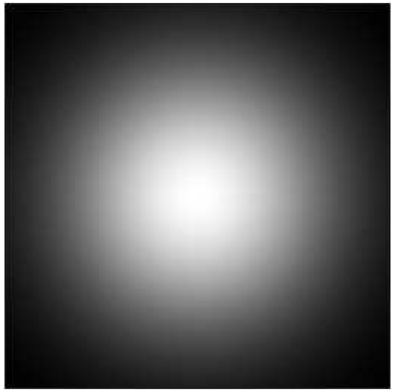






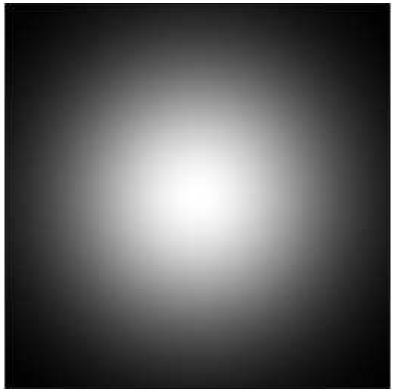
From 32 bits to 8 bits

32 bits



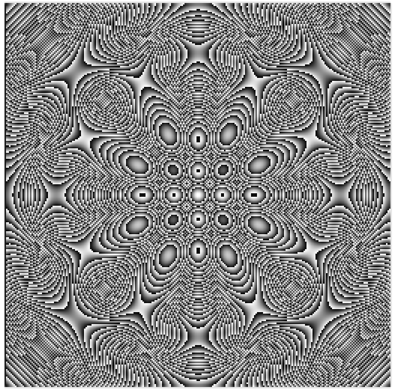
-

32 bits→8bits→32bits



=

Difference



Error some %

In practice

- **Image must be corrected**
  - **"Dark image" = Dark current of the CCD**
  - **"Flat-field image" = beam and optics image**

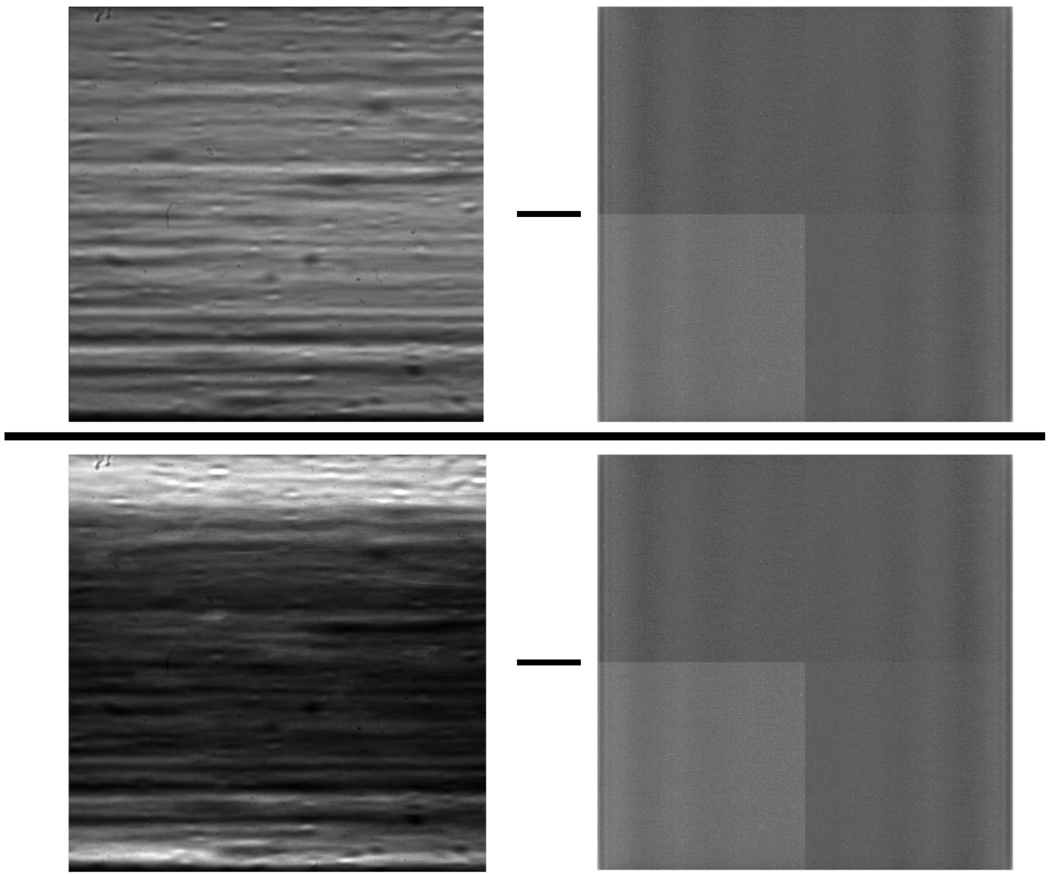
$$\mathbf{Image_{corrected} = (Image\text{-}Dark)/(Flat\text{-}Dark)}$$

  - **Attenuation image**

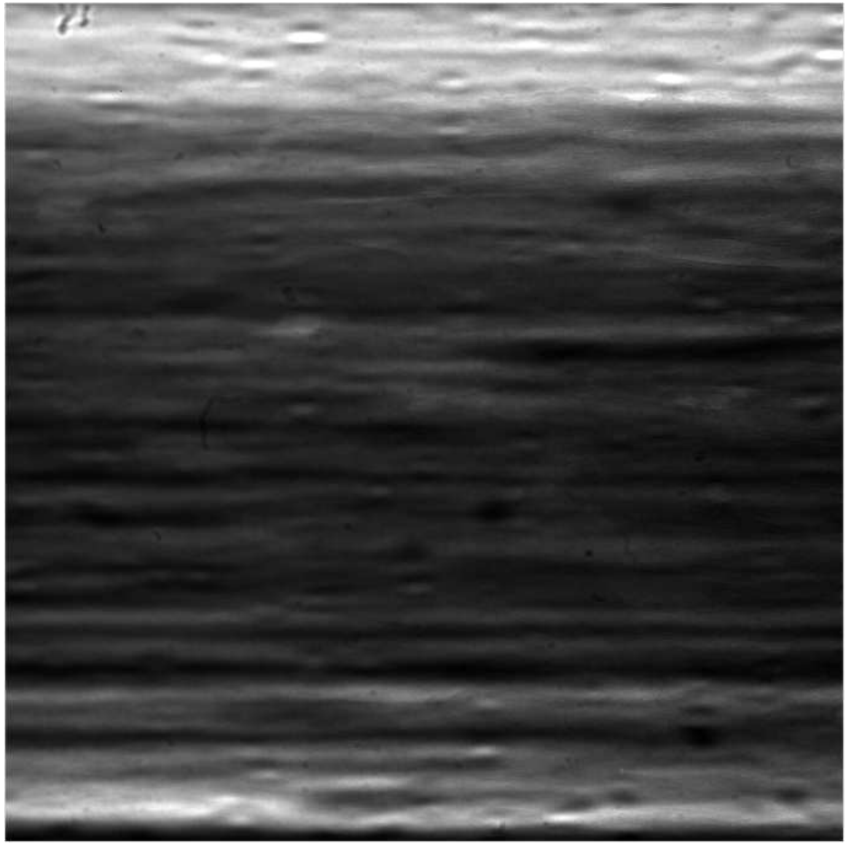
$$\mathbf{Image_{corrected}} = \mathit{ln}\ \mathbf{(Flat\ \text{-}Dark)/(Image\text{-}Dark)}$$

In practice

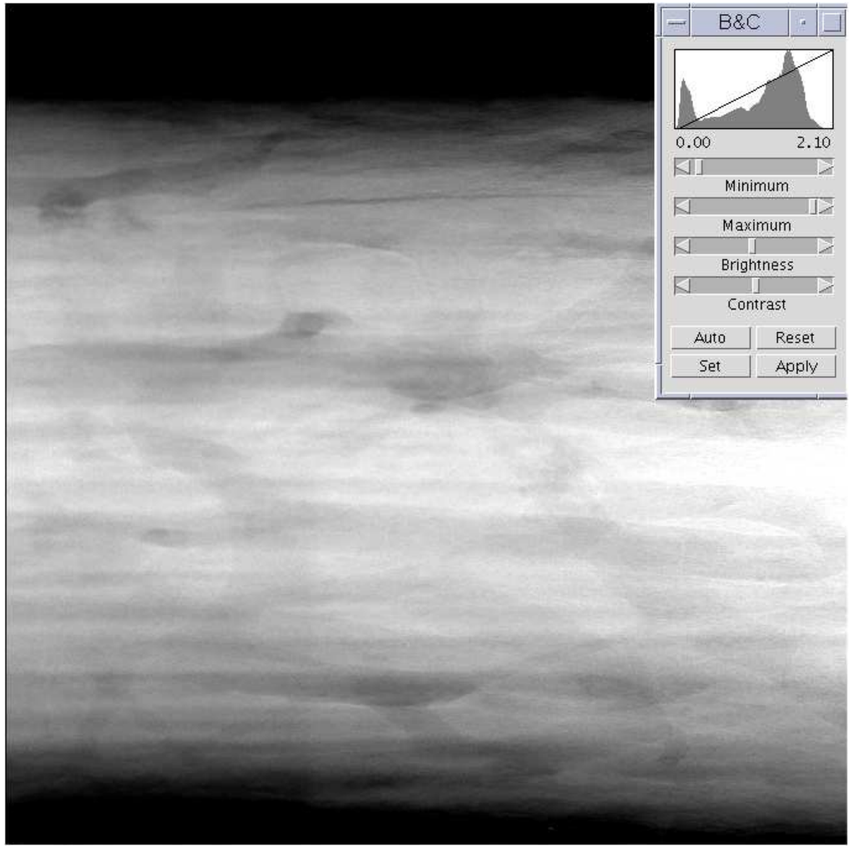
$\mathbf{Image_{corrected}} = \boldsymbol{ln}$



In practice



Before correction



After correction

Let's check :

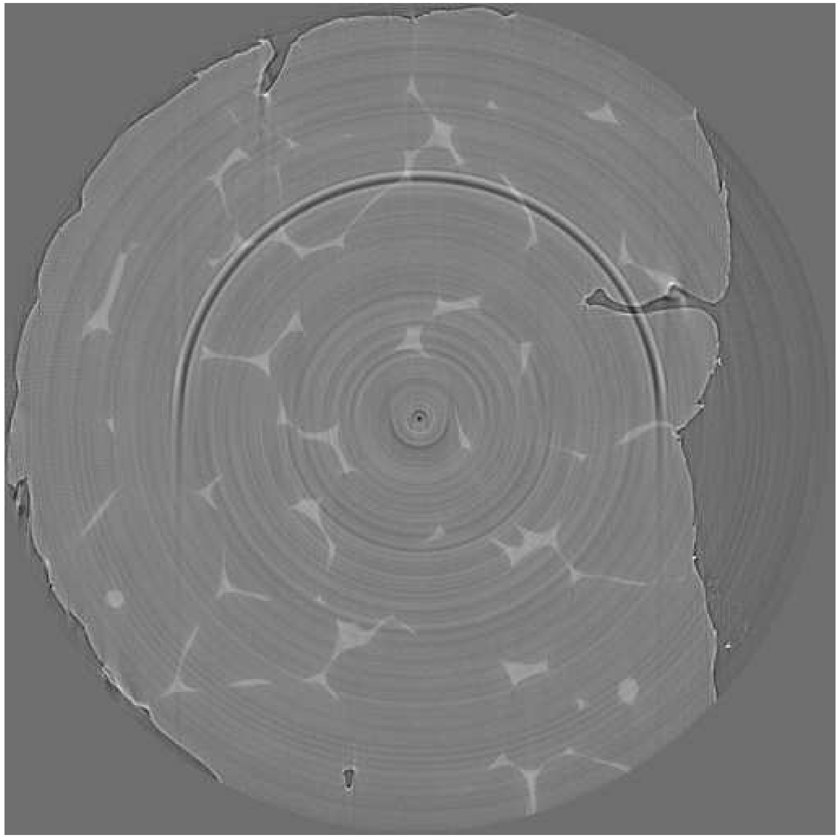
- **Sample = bone @15 keV (Images from BM05)** $\mu.l$**=17.34*0.12 = 2.08**

Ring artifacts

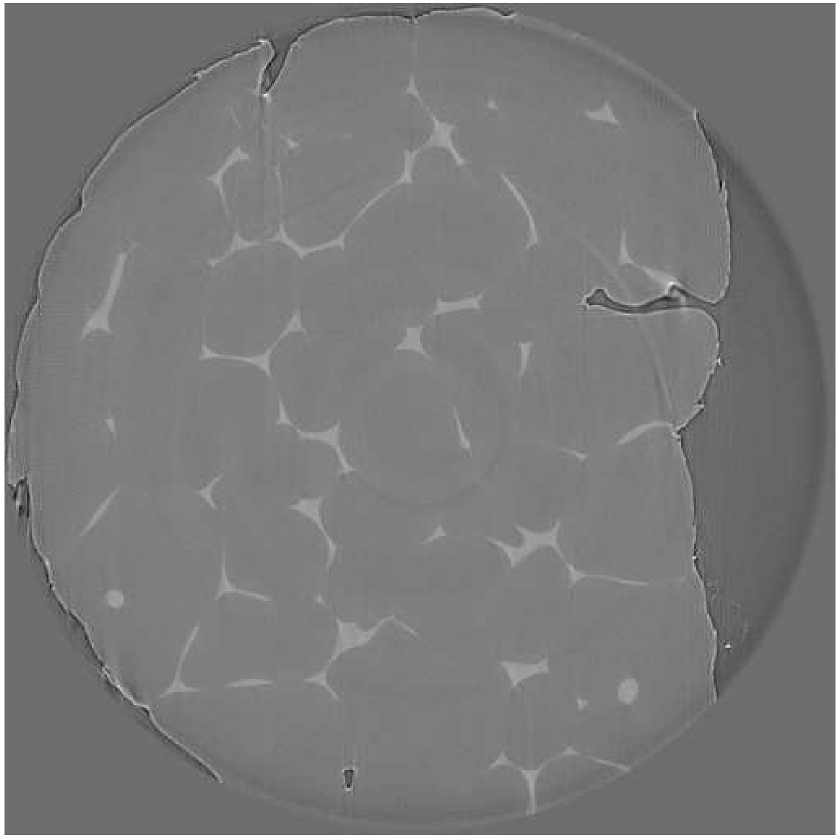
- **Causes**
  - **Beam instability (slow drift with time scale>exposure time)**
    - **"Easily" correctable by taking more flat field images**
  - **Defective or badly calibrated detector**
  - **Dead pixels**
    - **Single pixel ring artifacts**
- **Consequences**
  - **Wrong quantification**
  - **Esthetically not interesting**
  - **Loss of small structures**
  - **Acceptable in 2D, but complicates 3D visualisation**

Ring artifacts

Not corrected



Corrected

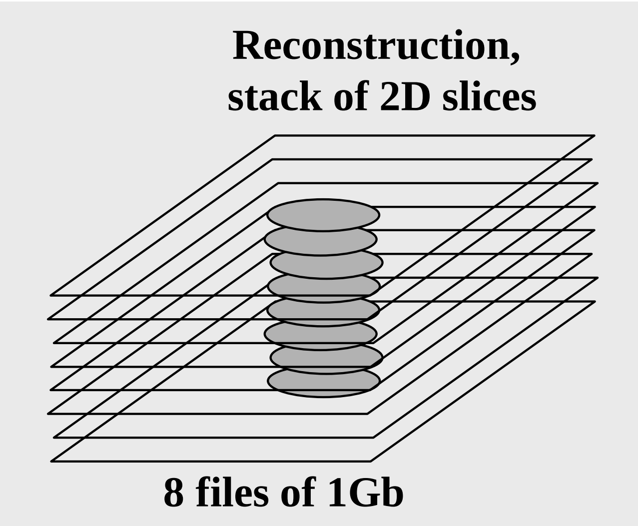


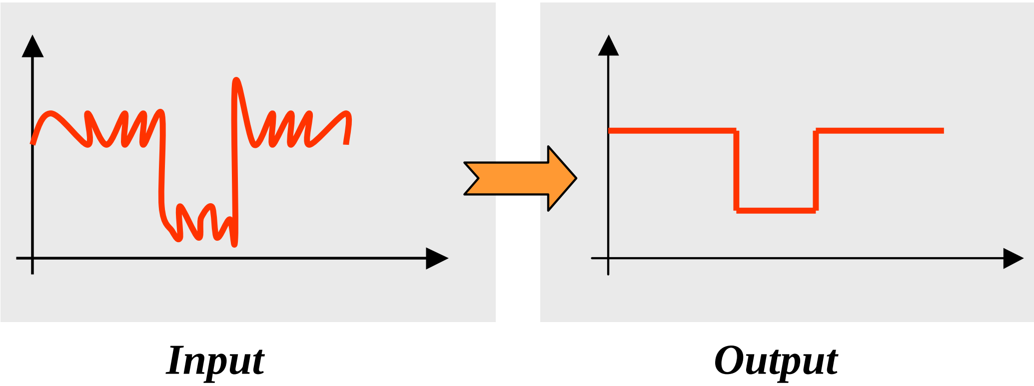
Images from L. Salvo et N. Limodin (GPM2) and P. Cloetens (ESRF)

Denoising

- **Noise causes**
  - **Misalignments**
  - **Sample motion**
  - **Radiation damage**
  - **Ring artifacts**
  - **Low statistics due to fast scanning**
  - **(…)**

Reconstruction denoising (ring artefacts, noise)

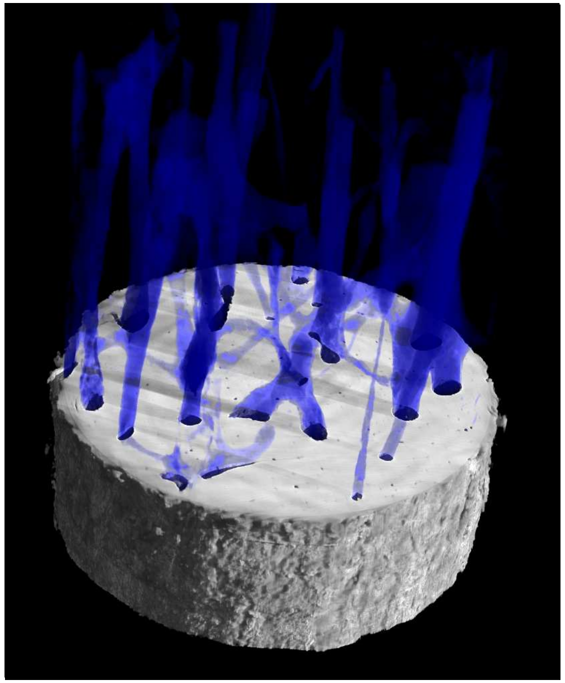




- **Multi-2D Filtering**
  - Possible, not always good
- **3D Filtering**
  - Not straightforward to create/manage a single file > 2Gb
  - Slow calculation (ImageJ, VGStudio) →C (ID19, ID22)

Sample characterisation

- **Basic image processing tools**
  - **Threshold**
  - **Segmentation (2D, multi-2D, 3D)**
  - **Porosity**
  - **Granulometry**
  - **(…)**



Sample characterisation

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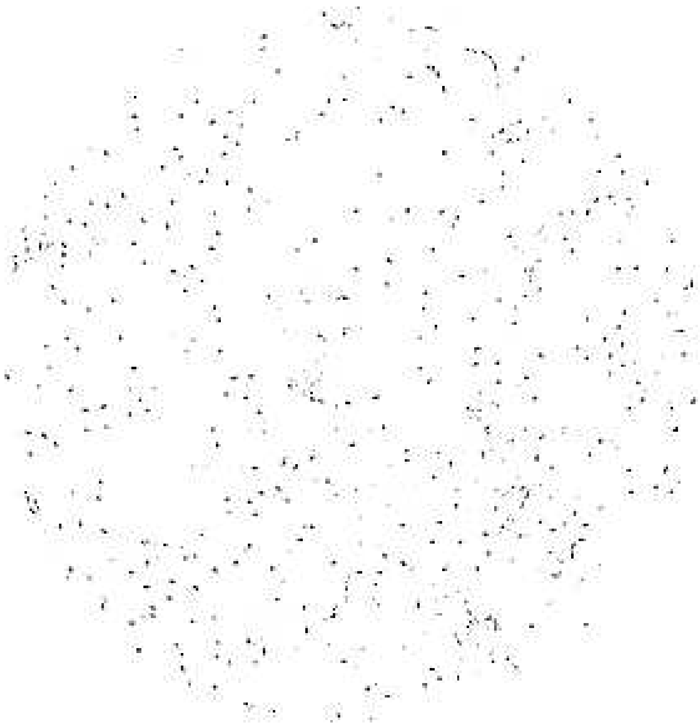

Sample characterisation

- **Basic image processing tools**
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  - Segmentation (2D, multi-2D, 3D)
  - **Porosity**
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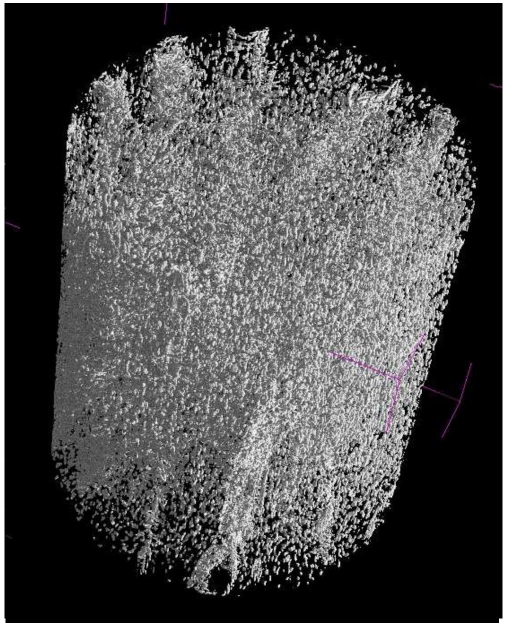
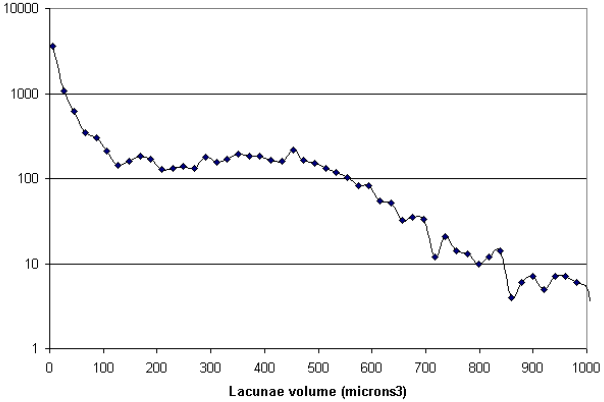
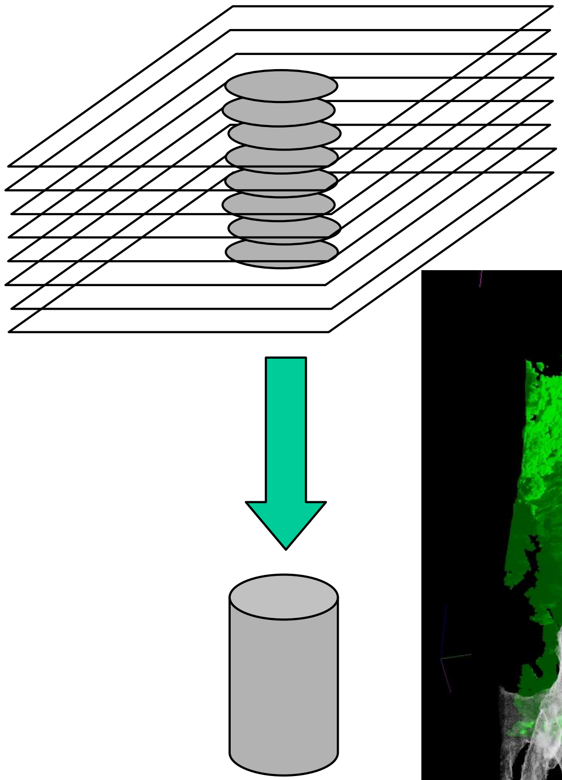
  - **(…)**

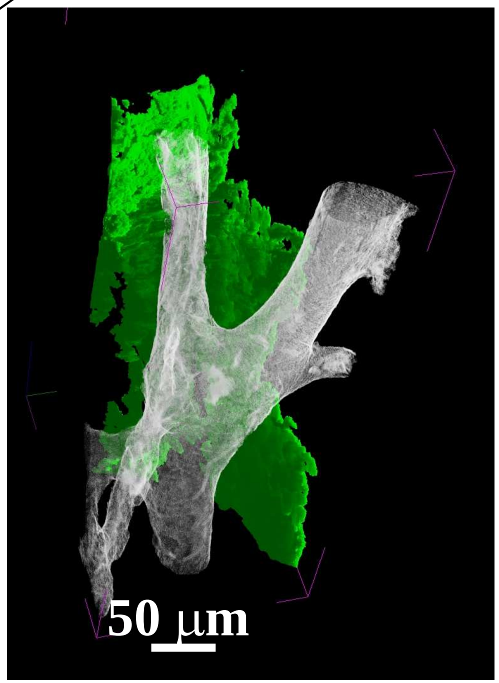




3D visualisation

Stack of 2D filtered slices





- **Software**
  - **VGStudiomax**
  - **Amira**
  - **(…)**
- **Issues**
  - **Memory allocation**
  - **Crash**
  - **Number licenses @ ESRF**

Talk outline

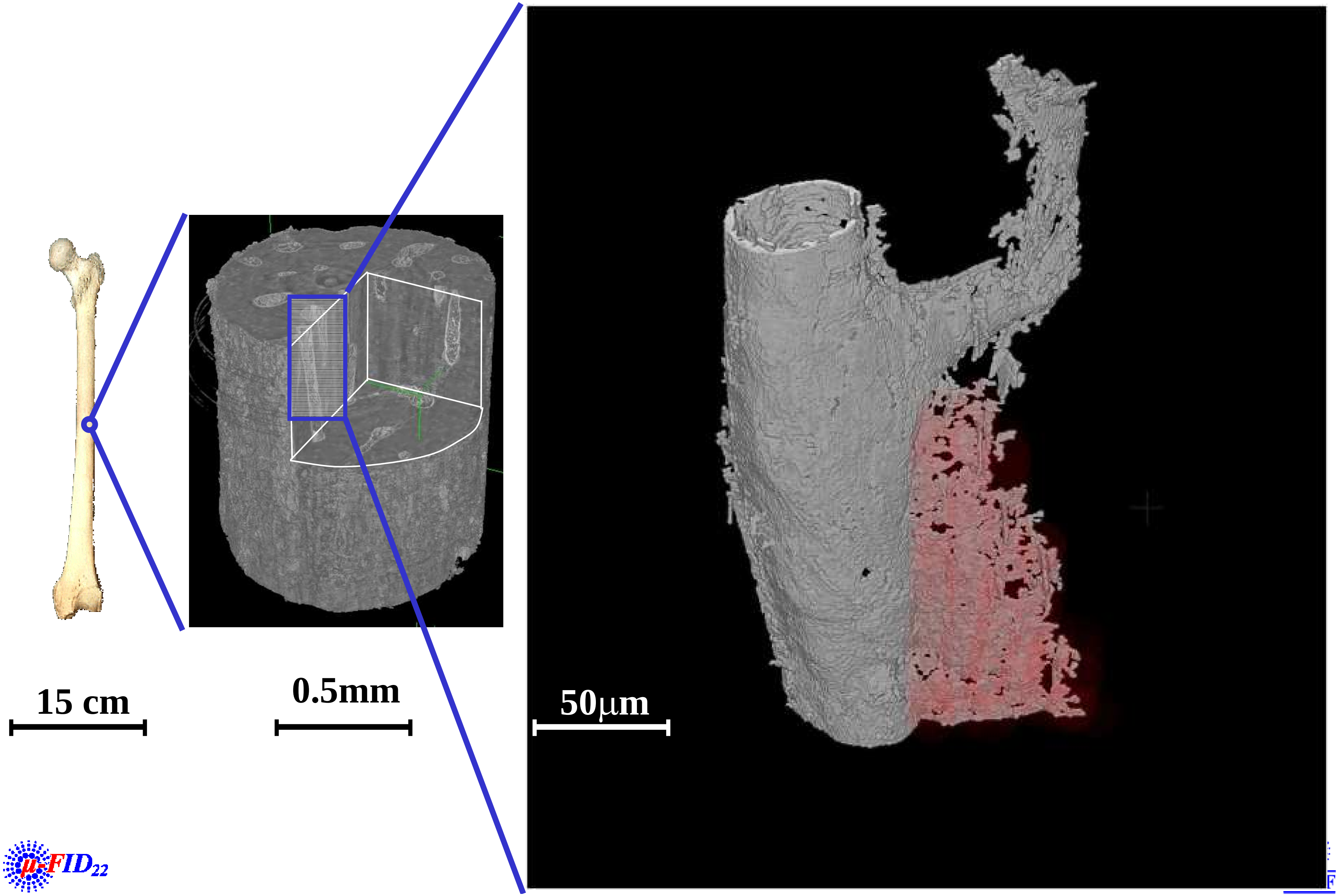
- **Introduction**
- **Absorption Imaging Background**
  - **0D→1D→2D→3D**
  - **Reconstruction basics**
- **Practical considerations**
  - **Alignment**
  - **Acquisition**
  - **Artifacts and artifact correction**
  - **Computing issues**
- **Some examples**
- **Concluding Remarks**

2D + t

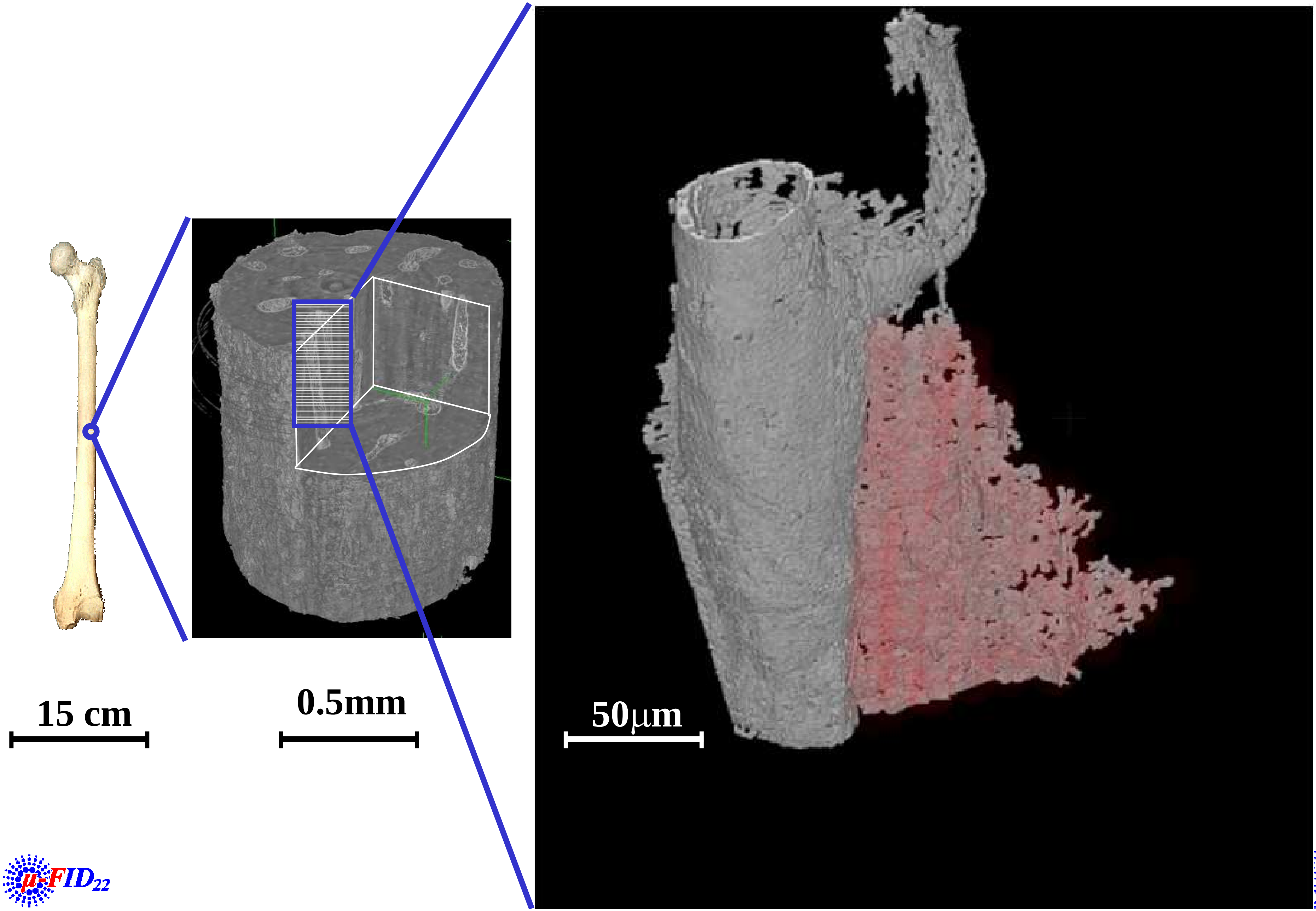
• 2-D Time resolved Imaging

Real Time Image of dendritic solidification of an Sn-Pb alloy melt
ME-595
Mathiesen et al.,Mat. Sci. and Eng., 2005

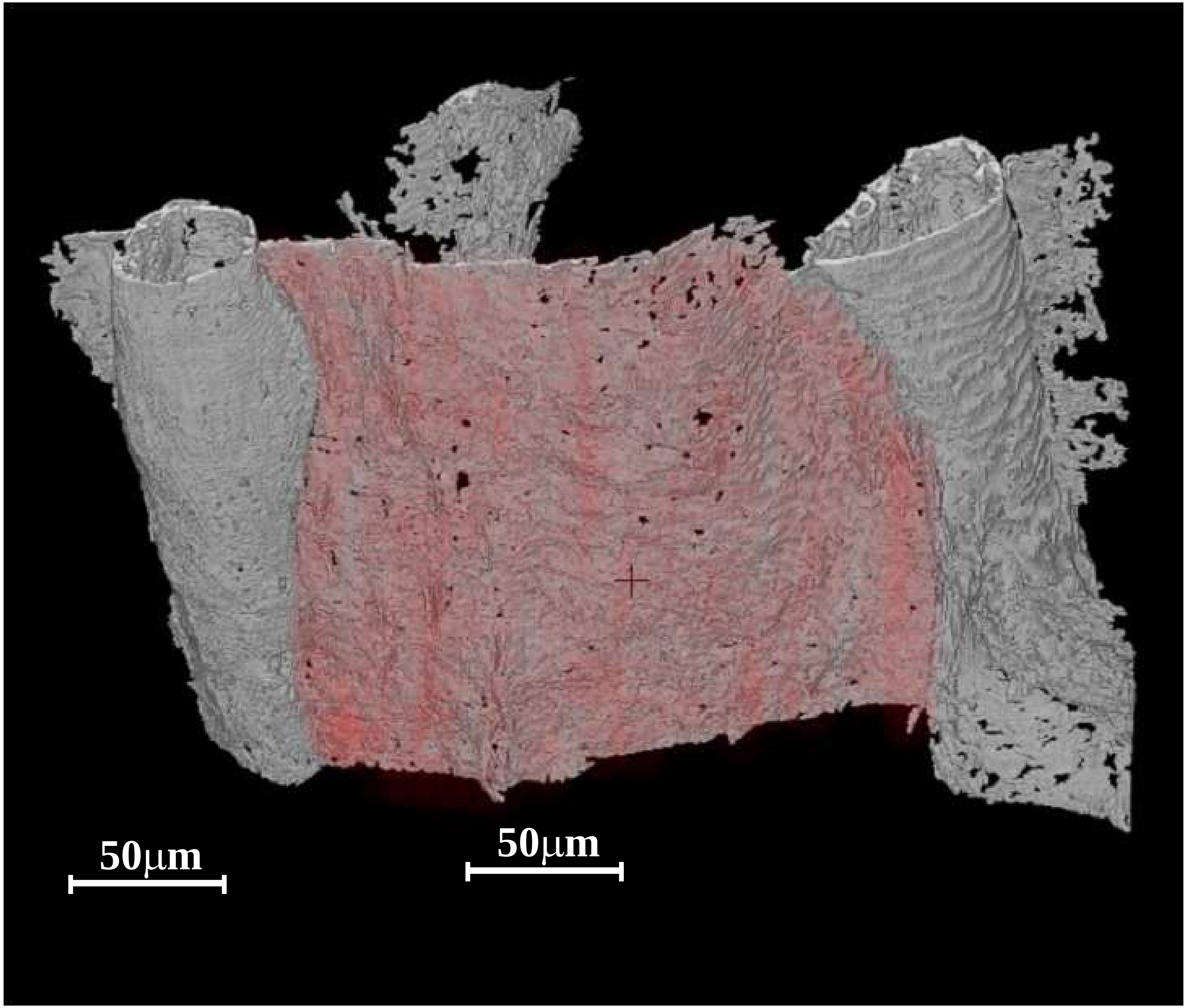
26 Mpa



40 Mpa



88 Mpa



Conclusion : Full sample characterization

Non destructive analysis

Internal structure

Internal elemental distribution

Quantification

Sample

(Sub)Micron resolution

In-situ

Trace element

3D

X-ray tomographic methods are potentially able to provide us with these information